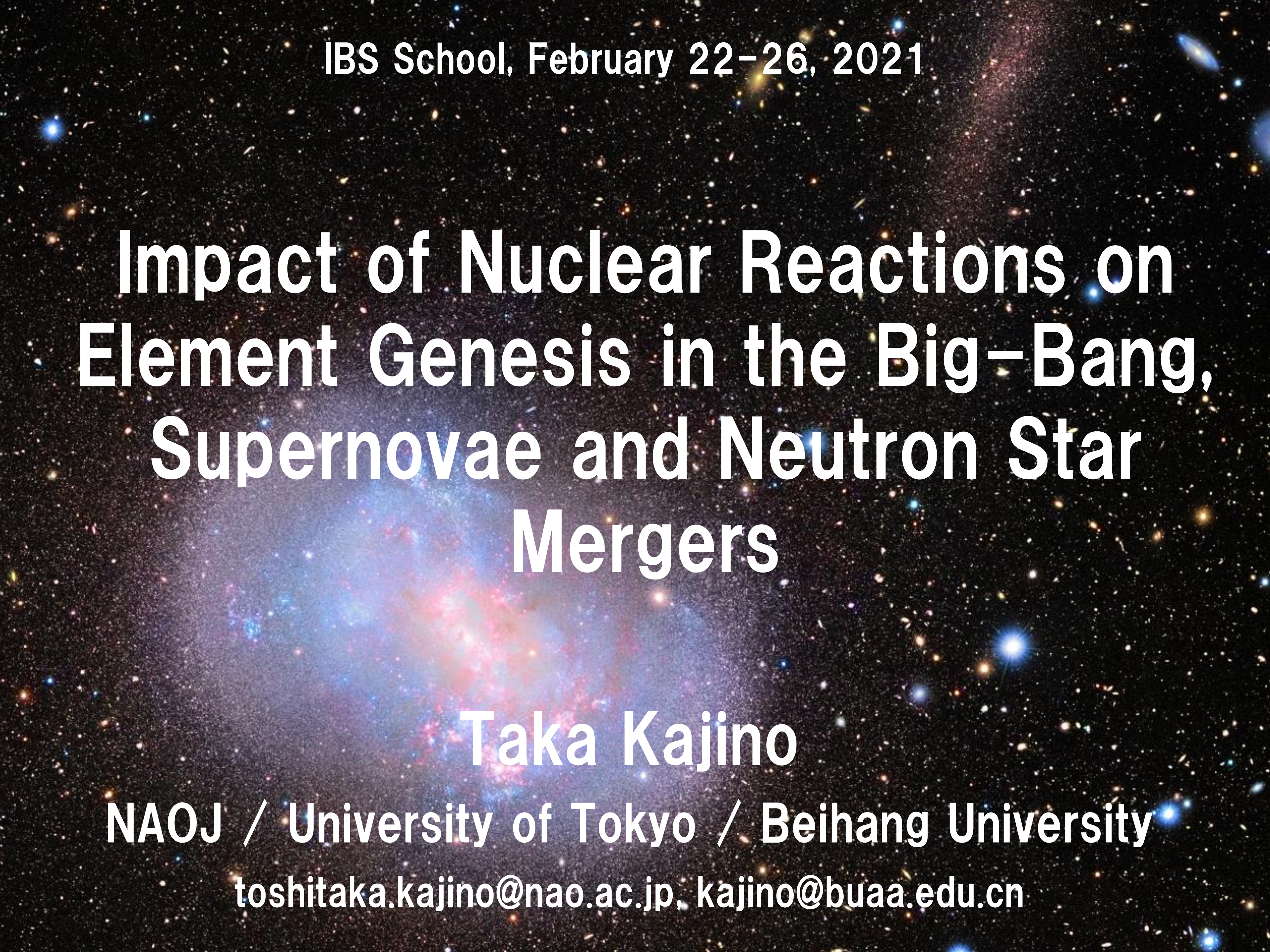


IBS School, February 22-26, 2021

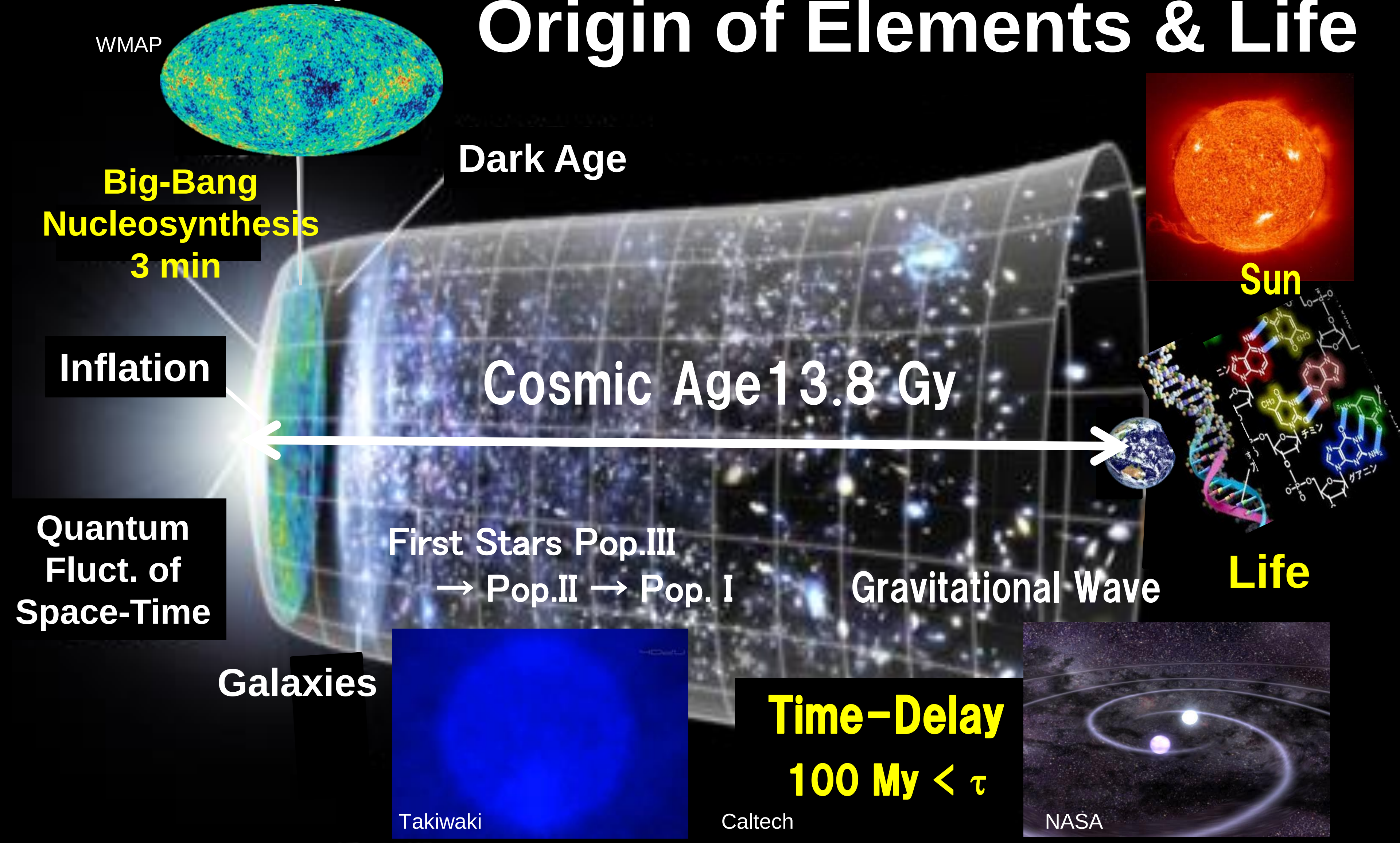
Impact of Nuclear Reactions on Element Genesis in the Big-Bang, Supernovae and Neutron Star Mergers

Taka Kajino

NAOJ / University of Tokyo / Beihang University

toshitaka.kajino@nao.ac.jp, kajino@buaa.edu.cn

Cosmic Evolution, Origin of Elements & Life



CMB Fluctuation
3.8×10^5 y

WMAP

Big-Bang
Nucleosynthesis
3 min

Dark Age

Inflation

Quantum
Fluct. of
Space-Time

Cosmic Age 13.8 Gy

Sun

Life

First Stars Pop.III
→ Pop.II → Pop. I

Gravitational Wave

Galaxies

Takiwaki

Supernova 1 My

Time-Delay
100 My < τ

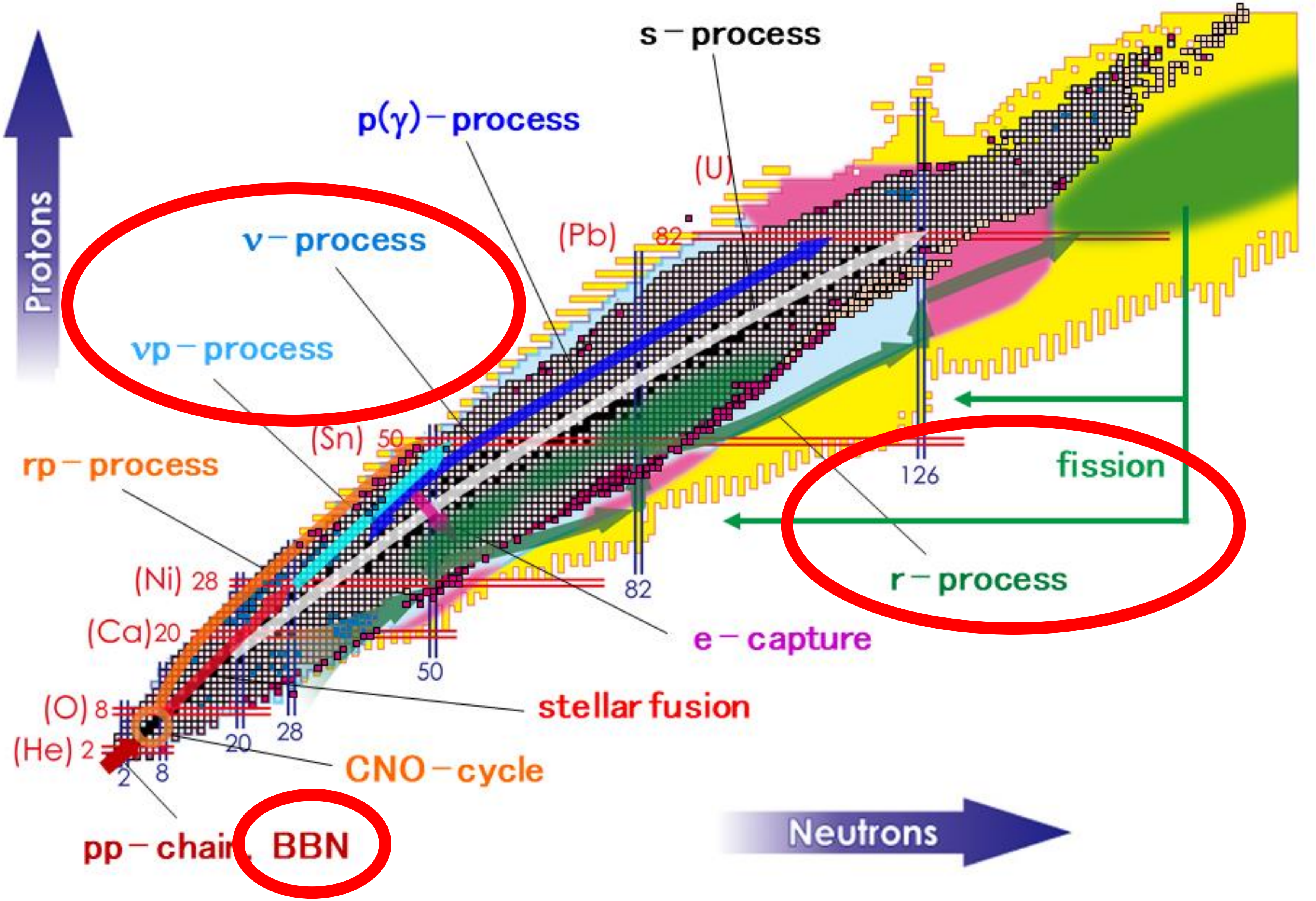
Caltech

NASA

Neutron Star Merger

Progress in Nuclear Astrophysics of Asia

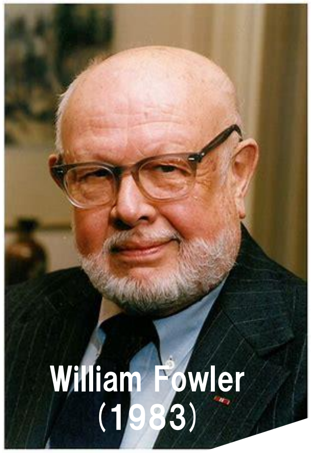
Ahmad, Ahn, Aoki, Aziz, Bhuyan, Chen, Guo, Hahn, Kajino, Kassim, Kim, Kubono, Kusakabe,
Li, Li, Li, Liu, Liu, Motobayashi, Pan, Park, Shi, Tang, Wang, Wen, Wu, Yan and Yusof,
AAPPS Bulletin (2021), to be published.

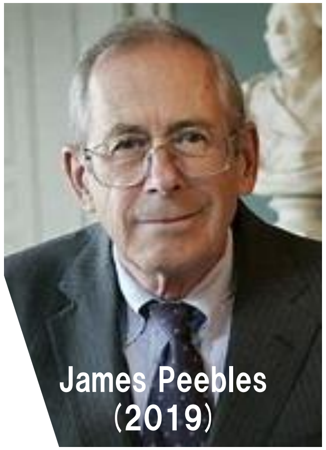


Dawn of "Multi-Messenger" Astronomy & Nuclear Astrophysics

GW —— **Nuclei** —— **ν** —— **Opt.-IR-X-γ**

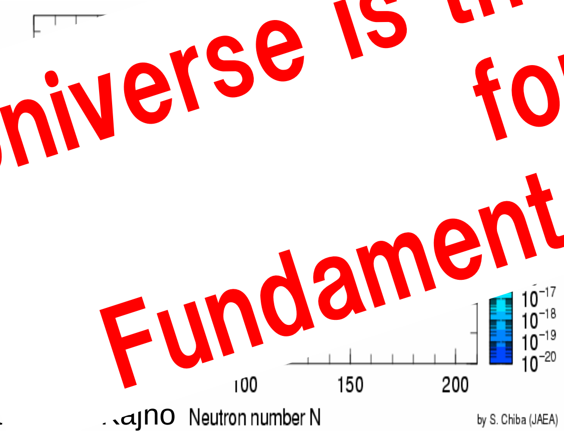
Gravity **Strong Nuclear Force** **Weak Force** **Electromagnetism**





Universe is the Laboratory for Fundamental Physics !

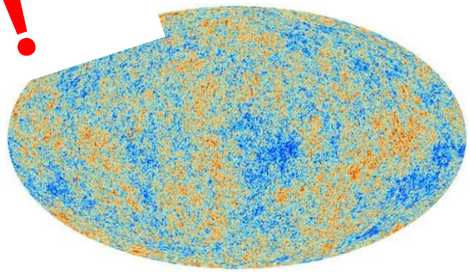
Caltech



Chiba

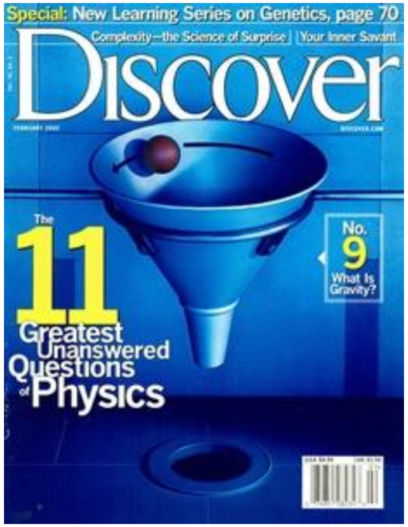
ajno

Takiwaki



Planck

Science in the 21st Century, is made on the SYNERGY among Nuclear Astrophysics, Cosmology, Space Science & Astronomy !



What is the Challenge of the Century？

The 11 Greatest Unanswered Questions in Physics !

The National Research Council's Board on Physics, USA (2002)

Resolution of these profound questions could unlock the secret of existence and deliver a new age of science.

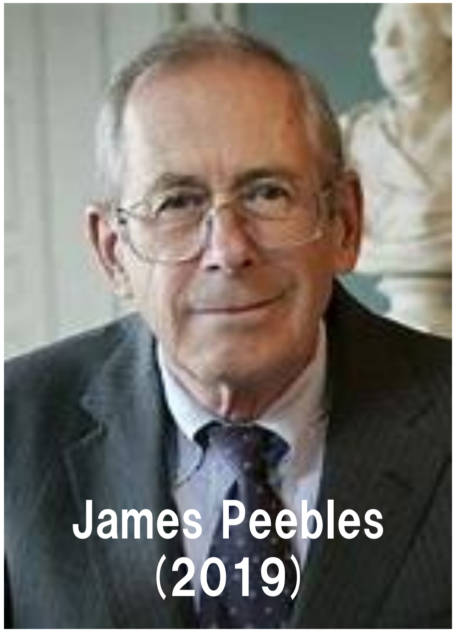
★ **Question 1 What is dark matter?**
★ **Question 2 What is dark energy?**
★ **Question 3 How were the heavy elements from iron to uranium made?**
★ **Question 4 Why do neutrinos have mass?**
★ **Question 5 Where do ultrahigh-energy particles come from?**
Question 6 Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
★ **Question 7 Are there new states of matter at ultrahigh temperatures and densities?**
Question 8 Are protons unstable?
★ **Question 9 What is gravity?**
★ **Question 10 Are there additional dimensions?**
★ **Question 11 How did the universe begin?**

Content

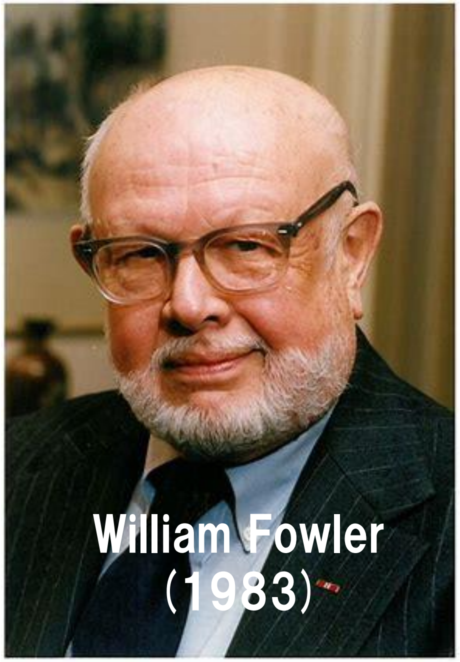
1. Big-Bang Cosmology

2. Supernova and Merger

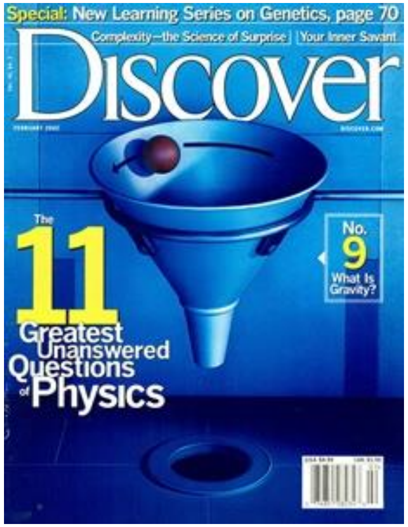
3. ν -Oscillation



James Peebles
(2019)



William Fowler
(1983)



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News! June 17, 2020

Physicists Announce
Potential Dark Matter Breakthrough

Axion !?

Xenon Collaboration's DM detector @ Gran Sasso

Axion, as a Dark Matter Candidate

QCD – Strong CP Problem

Although QCD Lagangian (i.e. strong interaction) breaks CP symmetry, CP symmetry is NOT strongly violated experimentally (e.g. neutron dipole moment measurement).

⇒ Peccei-Quinn (1977) : U(1) is dynamically broken to restore CP symmetry.

$$L = L_0 + \frac{\theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{a\gamma} = -g_{a\gamma} \boldsymbol{E} \cdot \boldsymbol{B} a$$

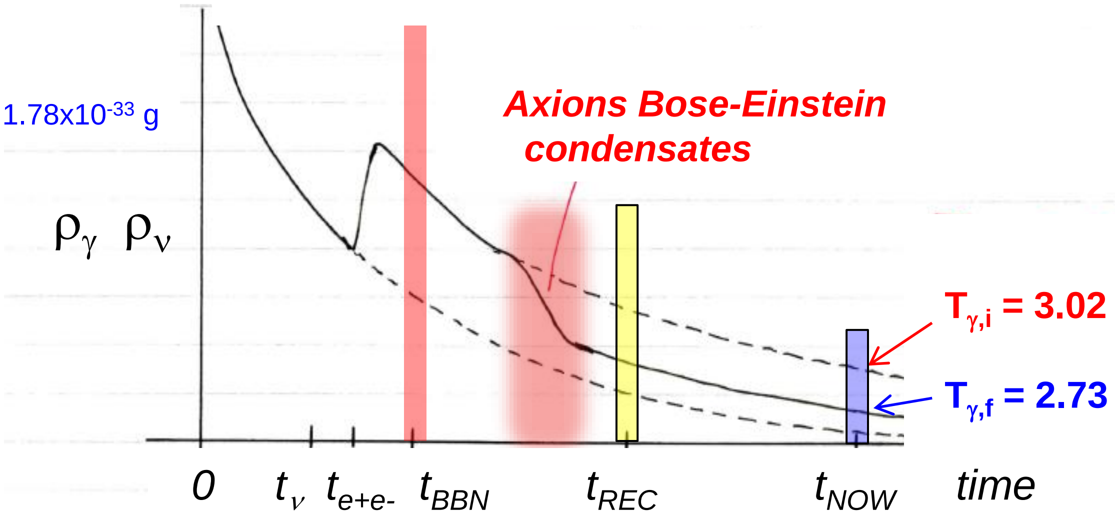
$$m_a = 0.62 \times 10^{-5}\,\mathrm{eV} \left(\frac{F_a}{10^{12}\,\mathrm{GeV}} \right)^{-1}$$

$$10^{9-10}\,\mathrm{GeV} \lesssim F_a \lesssim 10^{12-13}\,\mathrm{GeV}$$

1 eV = 1.78×10^{-33} g

Cosmological Application

Erken, Sikivie, Tam & Yang, PRL 108 (2012), 061304.



ν-decoupling

e⁺e⁻-annihilation & γ-reheating

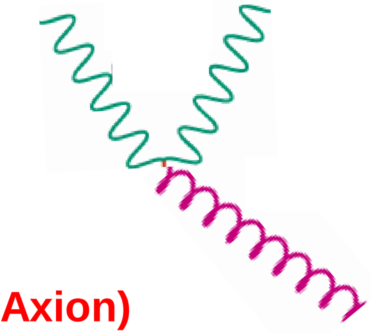
BBN (3min)

CMB Last-Photon scattering (3.8×10^5 yr)

$$\eta = n_B / n_\gamma$$

$$n_\gamma \propto T_\gamma^3$$

CBR-γ CBR-γ, reddening



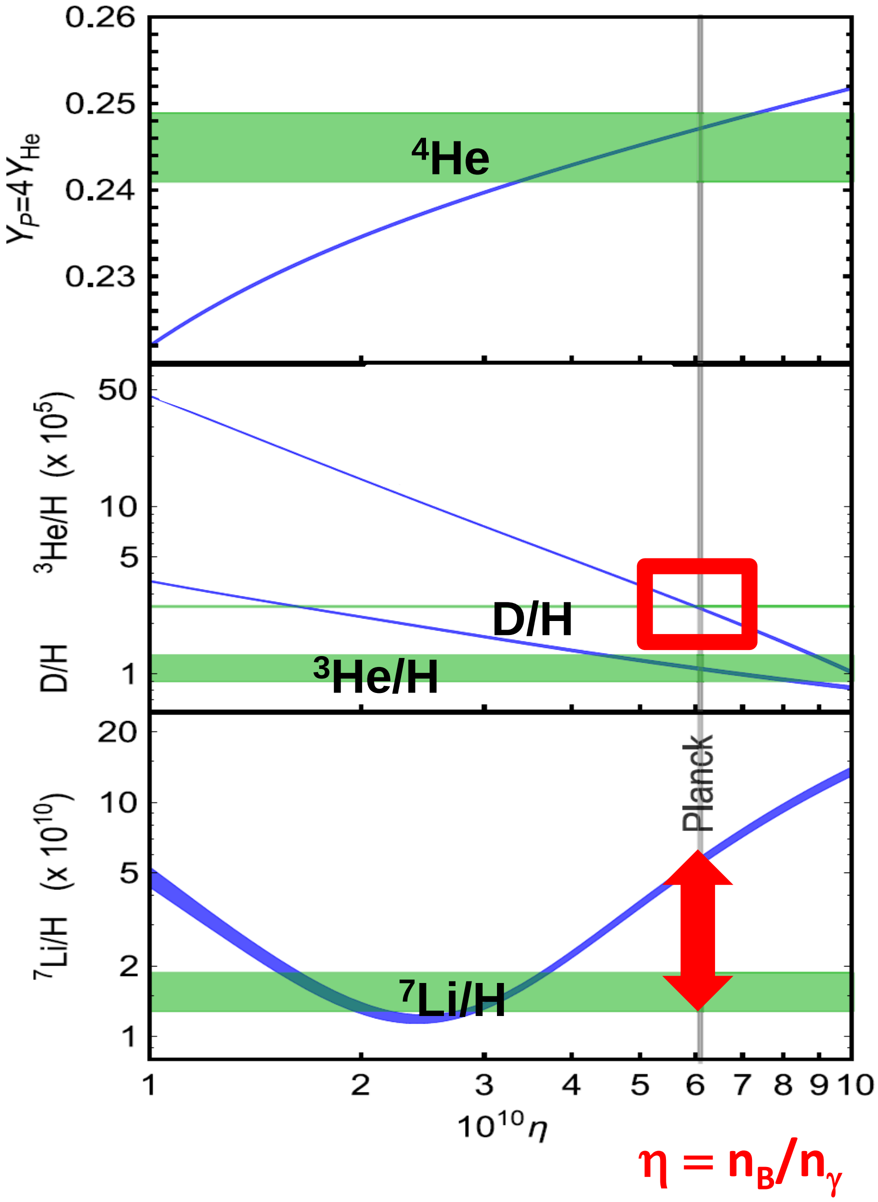
a (Axion)

Nambu-Goldstone Boson

➡ **Bose Einstein condensates!**

Big-Bang Nucleosynthesis, Precision Science ~1%

Pitrou, Coc, Uzan, Vangioni, PR 754 (2018), 1.



^{4}He :

n/p-ratio — Lifetime of UCN τ_n

AV-V coup. — Super-allowed β-decays

CKM Matrix — Unitarity

Mathews, Kajino, Shima, PR D71 (2005) 21302 (R).

D/H :

Obs. High-z Lyman Forests

Precise ~ 1% : 2.527 +/- 0.03 x 10 $^{-5}$

Cooke, Pettini, Steidel, ApJ 855 (2018), 102 (16pp).

Big-Bang D Tension ~ 1%

Big-Bang Li Problem ~ factor 3

Possible Solution ?

(1) New Physics (DM Particles …) ?

(2) Nuclear Physics ?

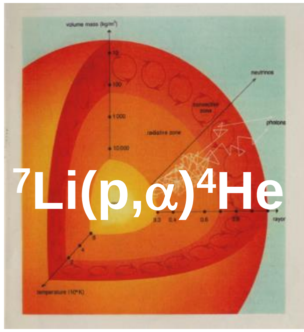
(3) Cosmological Effects ?

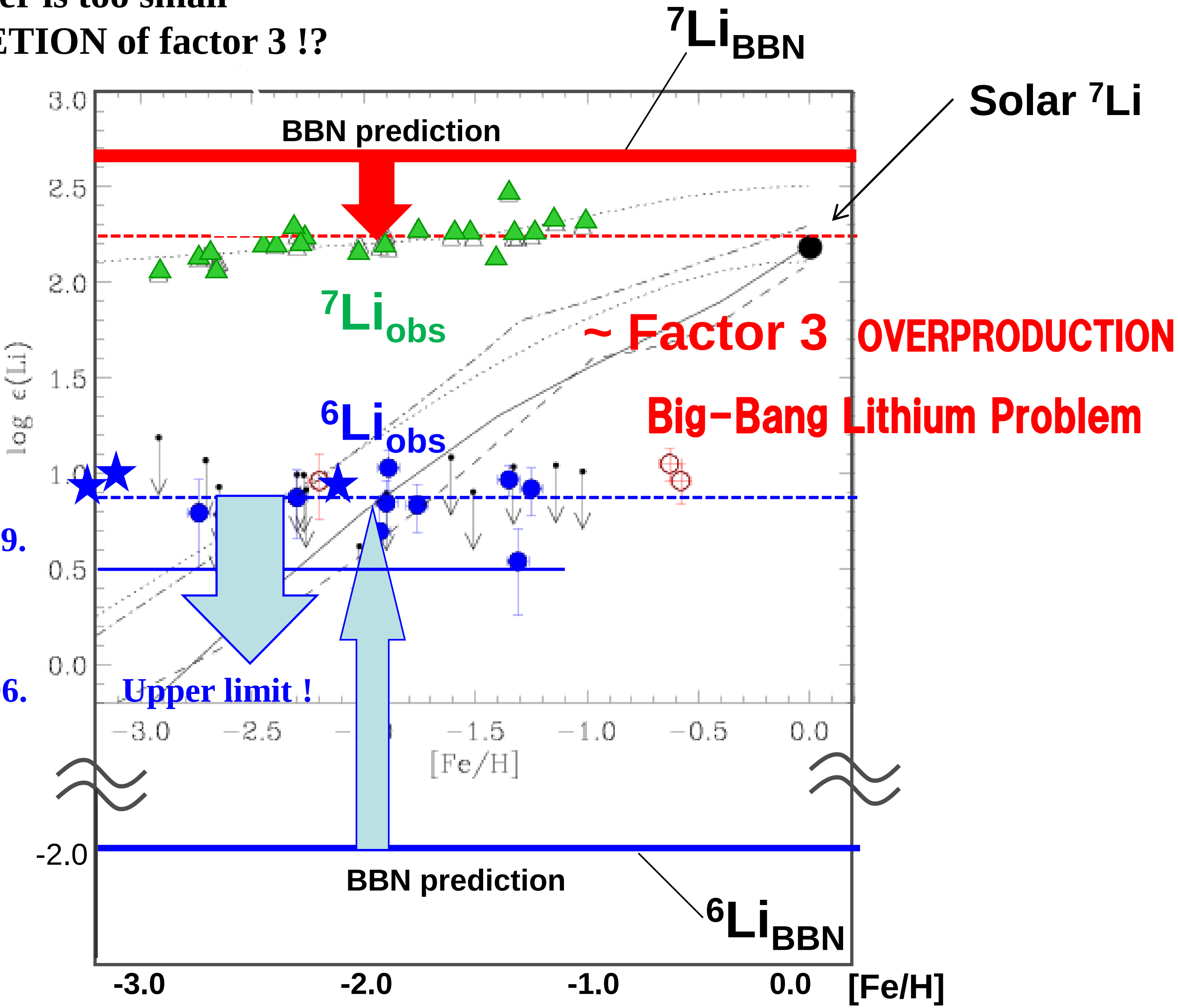
(CMB - Mag. Field Fluctuations) ?

Plateau like HIGH ^{6,7}Li ABUNDANCE --- primordial ?

Abundance scatter is too small
to accept DEPLETION of factor 3 !?

T = 1~3x10^6 K





~ Factor 3 OVERPRODUCTION

Big-Bang Lithium Problem

Asplund et al.,
ApJ 644 (2006) 229.

Lind et al.,
A&A 554 (2013) 96.

1. New physics solution ? — AXION ?

Axion
+
X^0-DM Model

Erken, Sikivie, Tam & Yang, PRL 108 (2012), 061304.

DM particle “axion”:

Bose-Einstein condensates and cool CMB-γ.

$$\boxed{\eta = n_B/n_\gamma, \quad n_\gamma \propto T_\gamma^3}$$

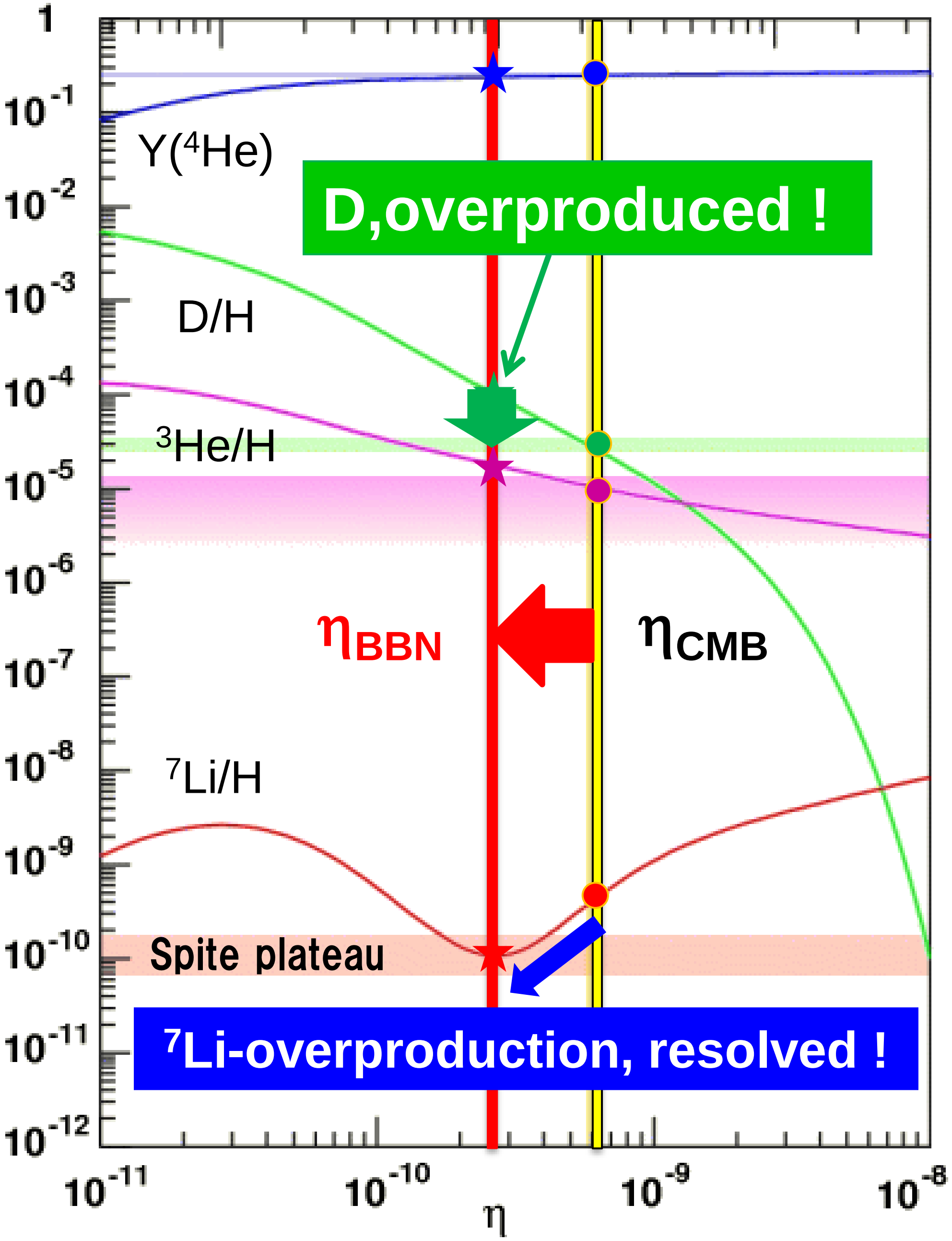
$$\eta_{BBN} < \eta_{WMAP}$$

Kusakabe, Balantekin, Kajino & Pehlivan, PL B718 (2013), 704 - 708.

“Axion” + SUSY DM particle
“stau X^0”:

decays to non-thermal photons γ_{NT}.

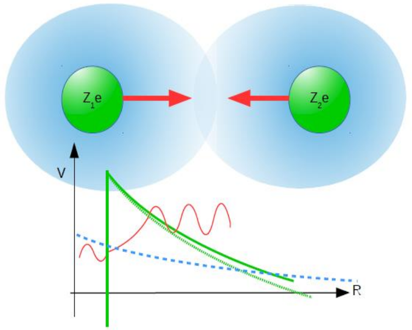
D is destroyed by $D(\gamma_{NT},n)p$!



D,overproduced !

^{7}Li-overproduction, resolved !

Electromagnetism & Plasma Screening in Nuclear Physics



- Nuclear Potential Perturbation
- Electrons in Boltzmann Distribution
- Poisson-Boltzmann Equation

Classical Thermal Nuclear Potential: Electron Background

$$\nabla^2\phi(r) = -4\pi Ze\delta(r^3) - 4\pi Zn_z e\exp\left[\frac{Ze\phi}{kT}\right]$$

$$+4\pi Zen_z\exp\left[\frac{-e\phi}{kT}\right]$$

$e\phi \ll kT \rightarrow$ First Order in Potential: Mod. Helm. Eqn.

$\phi(r) = \frac{Ze^2}{r}e^{-r/\lambda_D}$ Smaller $\lambda_D \rightarrow$ lower barrier.

$$\lambda_D \equiv \left(\frac{T}{4\pi e^2\sum_i(Z_i+Z_i^2)Y_i}\right)^{1/2}$$

Screening with FD Statistics: Poisson Equation with Pair Production

$$\nabla^2\phi = -4\pi Ze\delta(r^3) - 4\pi Zn_z e\exp\left[\frac{Ze\phi}{kT}\right]$$

$2\gamma \rightleftarrows e^+ + e^-$

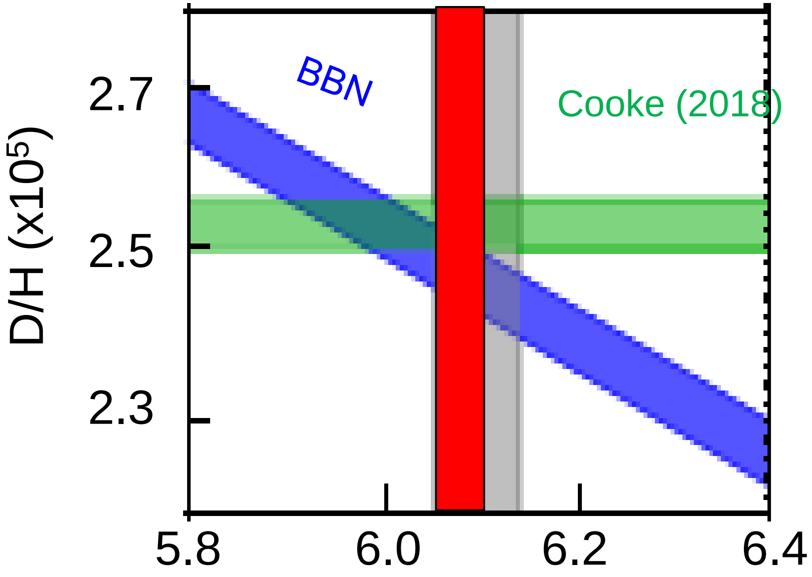
$$+Ze\int_0^\infty d^3p\left[\frac{1}{e^{(E-\mu-e\phi)/T}+1} - \frac{1}{e^{(E+\mu+e\phi)/T}+1}\right]$$

$$\frac{\pi^2}{\lambda^2} = e\frac{\partial n}{\partial\phi} = e\frac{\partial n}{\partial\mu} = e^2\frac{\partial}{\partial\mu}\int_0^\infty dpp^2\left[\frac{1}{e^{(E-\mu-e\phi)/T}+1} - \frac{1}{e^{(E+\mu+e\phi)/T}+1}\right]$$

Schwinger-Dyson Eq.: Kapusta (2006) ➡ Famiano, Balantekin, Kajino, PR C93 (2016), 045804.

Effects of Magnetic Field: Screening & Landau Quantization

Planck Coll. A&A 594, A13 (2016): h_{10} = 6.094 +/- 0.063
A&A 641, A6 (2020): 6.005 +/- 0.027

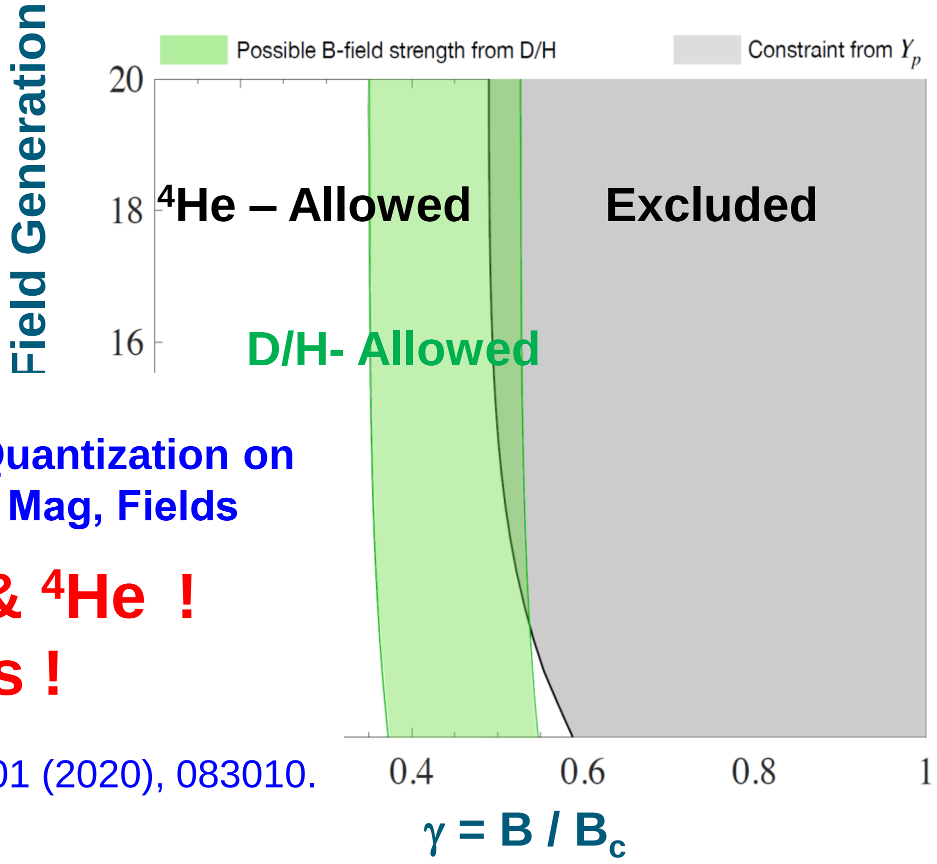


Mag. Field Strength

$\gamma = B / B_c$

$B_C = m_e^2/e$
$= 4.41 \times 10^{13}$ G

BBN with Prim. Mag. Field.



Effects of Relativistic e^+e^- Plasma + Landau Quantization on "Screening" & "Weak Decays" under Prim. Mag, Fields

No TENSION between D/H & ^{4}He !
Li Problem still remains !

Luo, Famiano, Kajino, Kusakabe, Balantekin, PR D101 (2020), 083010.

2. Nuclear physics solution ?

BBN Theory stands on precise nuclear physics?

Relevant nuclear reaction rates, ACCURATE enough within a few % ?

$^{7}\mathrm{Be}+n \rightarrow p_0+{}^{7}\mathrm{Li}_g,\ p_1+{}^{7}\mathrm{Li}^*,\ 2\,{}^{4}\mathrm{He}$

$^{7}\mathrm{Be}+{}^{3}\mathrm{He} \rightarrow {}^{10}\mathrm{C}^*$
$\rightarrow {}^{6}\mathrm{Be} + {}^{4}\mathrm{He}$
$\rightarrow {}^{9}\mathrm{B} + p$
$\rightarrow {}^{8}\mathrm{Be} + 2p$

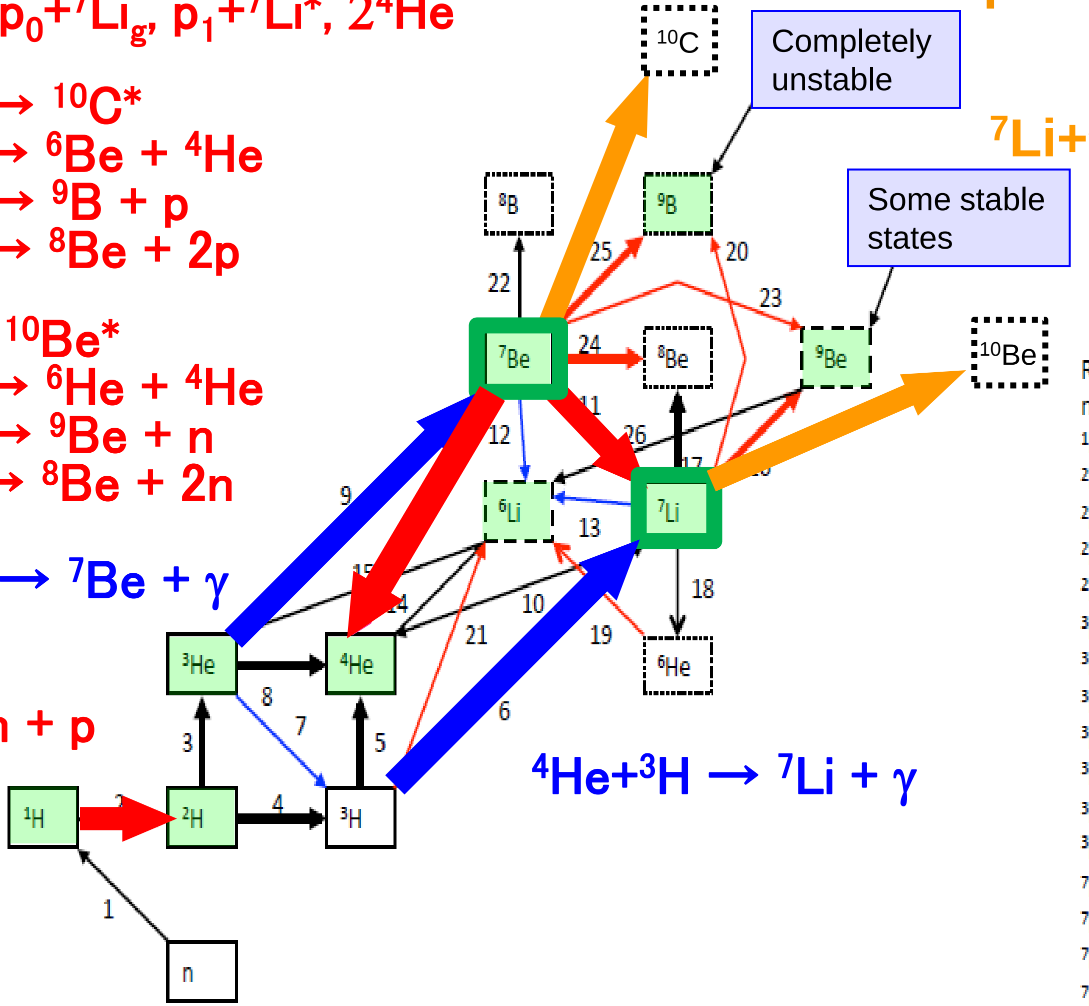
$^{7}\mathrm{Li}+{}^{3}\mathrm{H} \rightarrow {}^{10}\mathrm{Be}^*$
$\rightarrow {}^{6}\mathrm{He} + {}^{4}\mathrm{He}$
$\rightarrow {}^{9}\mathrm{Be} + n$
$\rightarrow {}^{8}\mathrm{Be} + 2n$

$^{4}\mathrm{He}+{}^{3}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

$D+\gamma \rightarrow n + p$

$^{7}\mathrm{Be}+{}^{3}\mathrm{He} \rightarrow {}^{10}\mathrm{C} \rightarrow 2p\alpha\alpha$

$^{7}\mathrm{Li}+{}^{3}\mathrm{H} \rightarrow {}^{10}\mathrm{Be} \rightarrow 2n\alpha\alpha$



$^{4}\mathrm{He}+{}^{3}\mathrm{H} \rightarrow {}^{7}\mathrm{Li} + \gamma$

Reaction Key	
$n \rightarrow {}^{1}H$	1
$^{1}H(n,g)^{2}H$	2
$^{2}H(^{2}H,n)^{3}He$	3
$^{2}H(^{1}H,g)^{3}He$	
$^{2}H(^{2}H,^{1}H)^{3}H$	4
$^{2}H(n,g)^{3}H$	
$^{3}H(^{2}H,n)^{4}He$	5
$^{3}H(^{1}H,g)^{4}He$	
$^{3}H(^{4}He,g)^{7}Li$	6
$^{3}He(n,^{1}H)^{3}H$	7
$^{3}He(^{2}H,^{1}H)^{4}He$	8
$^{3}He(n,g)^{4}He$	
$^{3}He(^{4}He,g)^{7}Be$	9
$^{7}Li(^{1}H,^{3}He)^{4}He$	10
$^{7}Be(n,^{1}H)^{7}Li$	11
$^{7}Be(n,^{2}H)^{6}Li$	12
$^{7}Li(n,2n)^{6}Li$	13

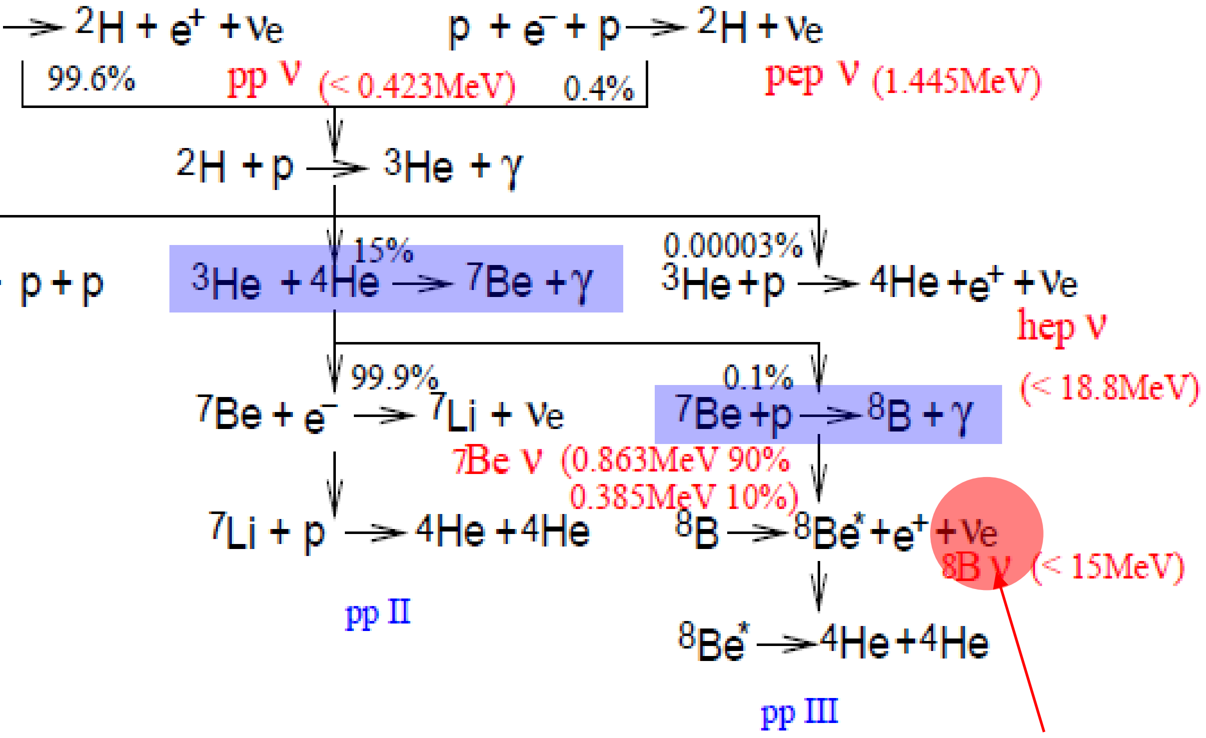
Reaction Key	
$^{4}He(^{2}H,g)^{6}Li$	14
$^{6}Li(^{1}H,^{4}He)^{3}He$	15
$^{7}Li(^{3}H,n)^{9}Be$	16
$^{7}Li(^{3}He,^{1}H)^{9}Be$	
$^{7}Li(^{2}H,n)^{8}Be$	17
$^{7}Li(^{1}H,g)^{8}Be$	
$^{7}Li(^{3}He,^{2}H)^{8}Be$	
$^{8}Be \rightarrow {}^{4}He+{}^{4}He$	
$^{7}Li(^{3}H,\ ^{4}He)^{6}He$	18
$^{6}He \rightarrow {}^{6}Li$ or $^{4}He+{}^{2}H$	19
$^{7}Li(^{3}He,n)^{9}B$	20
$^{3}He(^{3}H,g)^{6}Li$	21
$^{7}Be(^{1}H,g)^{8}B$	22
$^{7}Be(^{3}H,^{1}H)^{9}Be$	23
$^{7}Be(^{2}H,^{1}H)^{8}Be$	24
$^{7}Be(^{3}H,^{2}H)^{8}Be$	
$^{7}Be(^{3}He,^{1}H)^{9}B$	25
$^{7}Be(^{3}H,n)^{9}B$	
$^{9}Be(^{1}H,^{4}He)^{6}Li$	26

Solar Fusion Reaction — p-p Chains

Missing Solar Neutrino Puzzle

W. Fowler predicted (1958): R. Davis' Cl-detector (1969～), GALLEX, SK, SNO, etc.

Detecting solar neutrinos is the evidence for solar fusion!



$p + p \rightarrow {}^2H + e^+ + \nu_e$ 99.6% pp ν (< 0.423MeV)

$p + e^- + p \rightarrow {}^2H + \nu_e$ 0.4% pep ν (1.445MeV)

${}^2H + p \rightarrow {}^3He + \gamma$

85% ${}^3He + {}^3He \rightarrow {}^4He + p + p$

pp I

15% ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

0.00003% ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ hep ν (< 18.8MeV)

99.9% ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$ 7Be ν (0.863MeV 90% 0.385MeV 10%)

${}^7Li + p \rightarrow {}^4He + {}^4He$

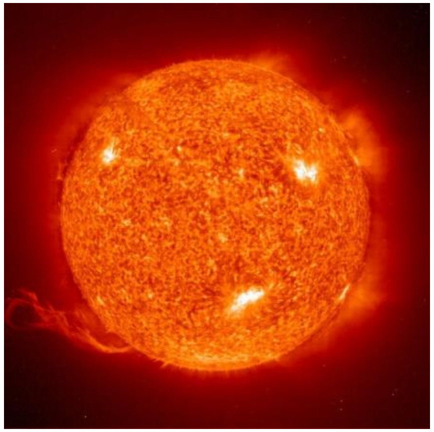
pp II

0.1% ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$ 8B ν (< 15MeV)

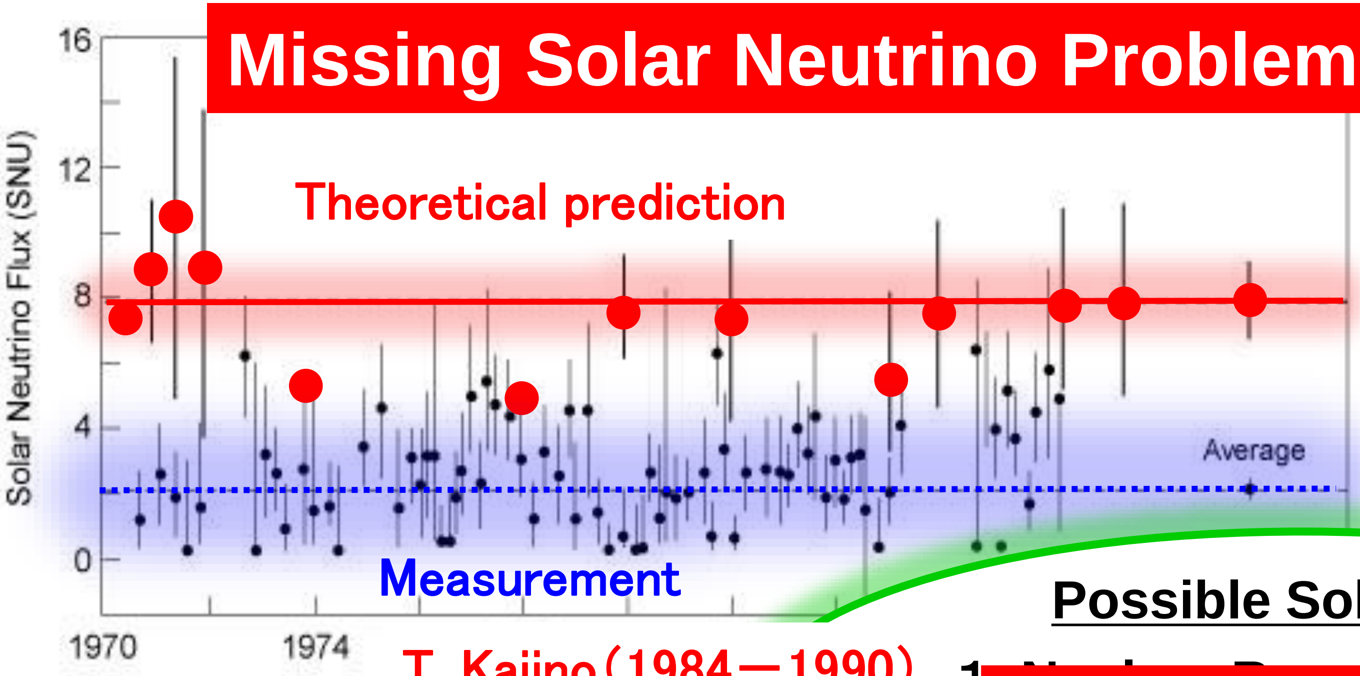
${}^8Be^* \rightarrow {}^4He + {}^4He$

pp III



Most energetic (<15MeV) neutrinos !

Missing Solar Neutrino Problem



Jr.

ics

ysics

1983)

T. Kajino（1984－1990）

J. Bahcall（1988）

Possible Solution？

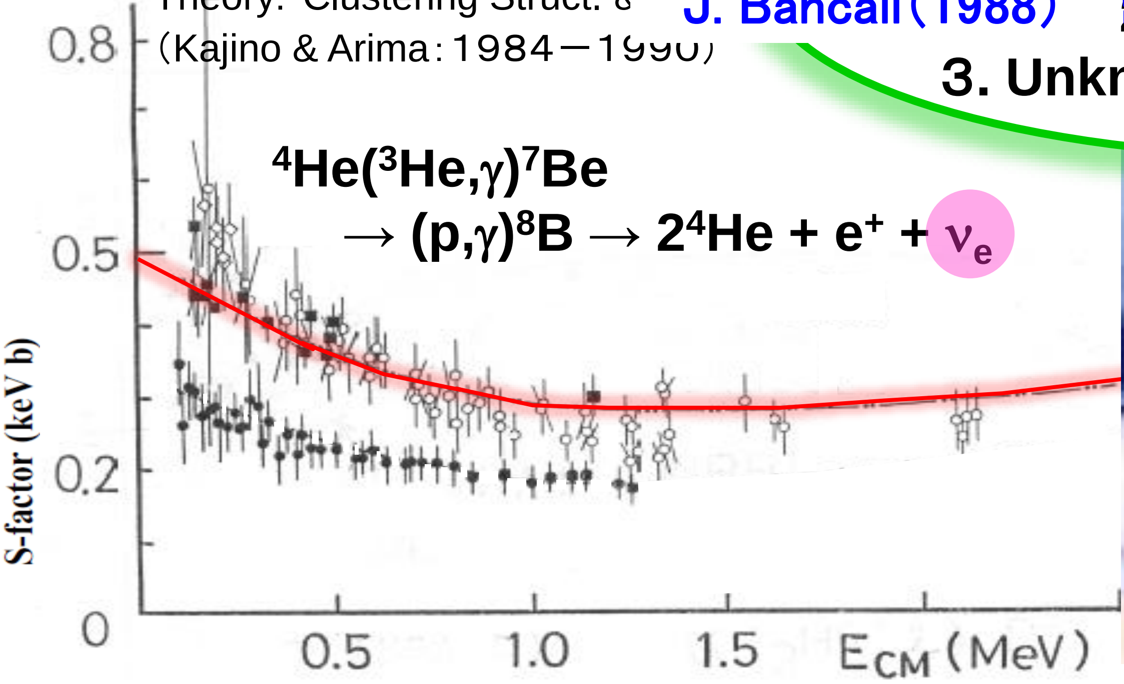
~~1. Nuclear Reaction Rates?~~

~~2. Solar Model?~~

3. Unknown Neutrino Nature?

Theory: Clustering Struct. &

（Kajino & Arima：1984－1990）



$^4He(^3He,\gamma)^7Be$

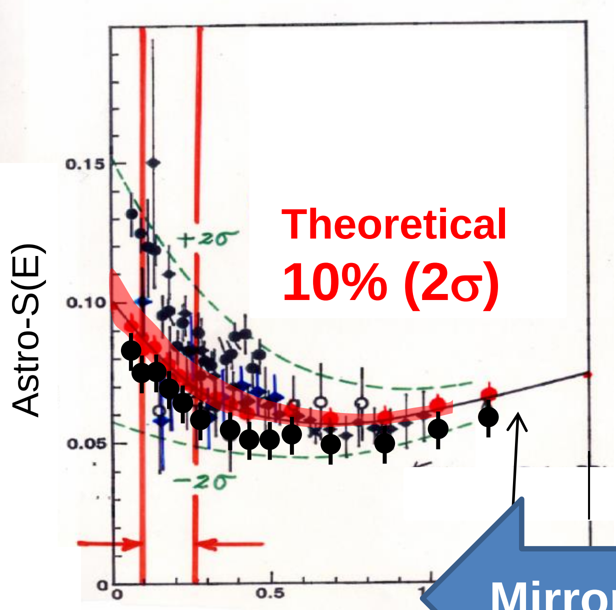
$\rightarrow (p,\gamma)^8B \rightarrow 2\,^4He + e^+ + \nu_e$

^{4}He(^{3}H,γ)^{7}Li ⟷ Mirror Conjugation ⟷ **^{4}He(^{3}He,γ)^{7}Be**

Adelberger, RMP 83 (2011),195.

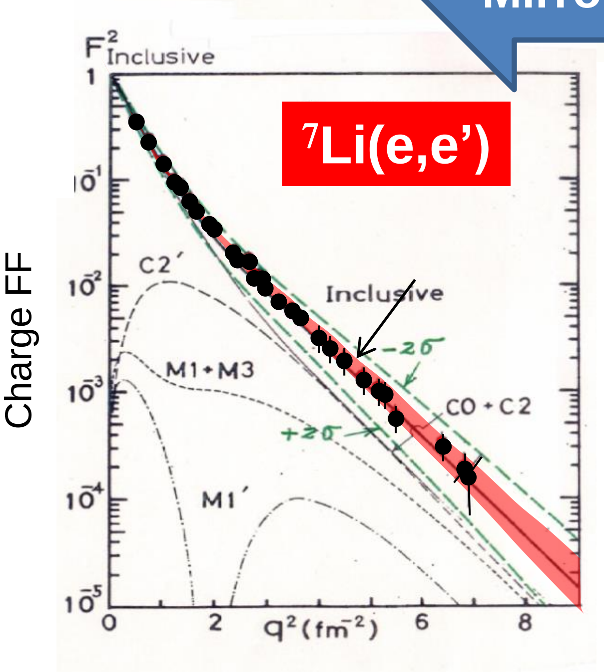
5% (1σ), accurate !? ➡ **Still more than 25% uncertain !**

Kajino & Arima, PRL 52 (1984), 739; NP A413 (1084), 323; NP A460 (1986), 559; ApJ 319 (1987), 531, Neff, PRL 106 (2011), 042502, Dohet-Early et al., PL B757 (2016), 430; Vorabbi et al., PR C100 (2019), 024304



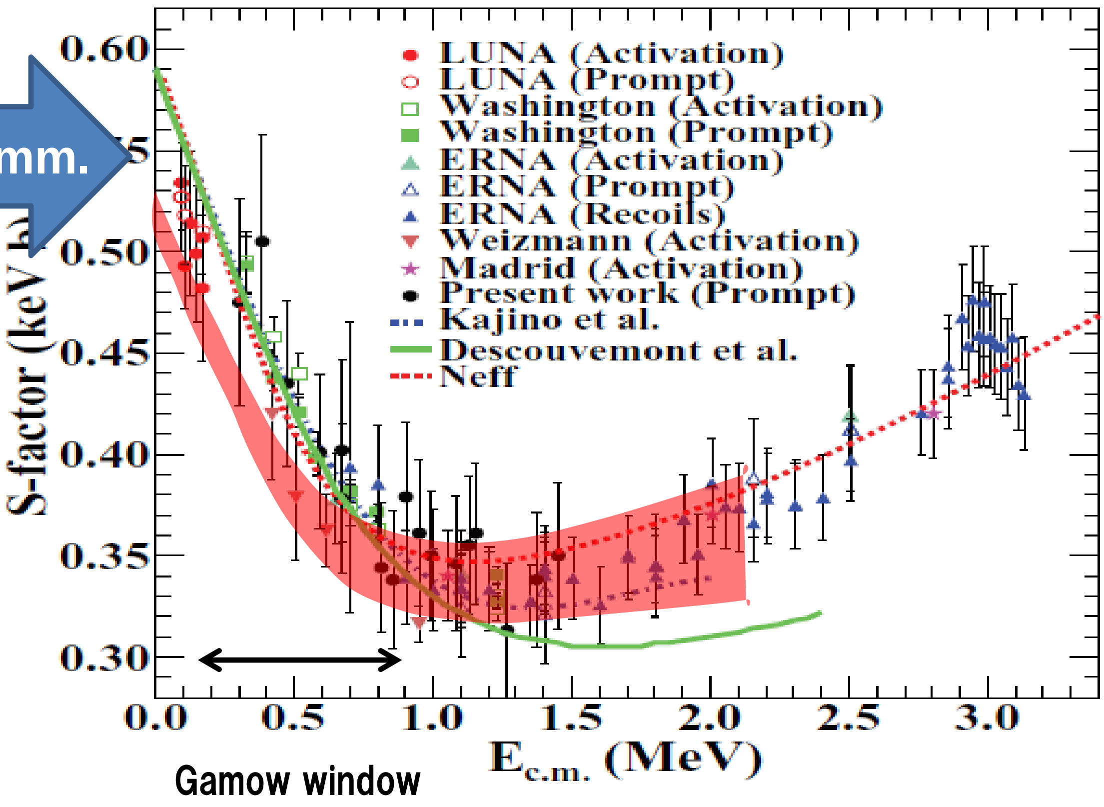
Theoretical 10% (2σ)

Mirror Symm.



^{7}Li(e,e')

^{4}He(^{3}He,γ)^{7}Be



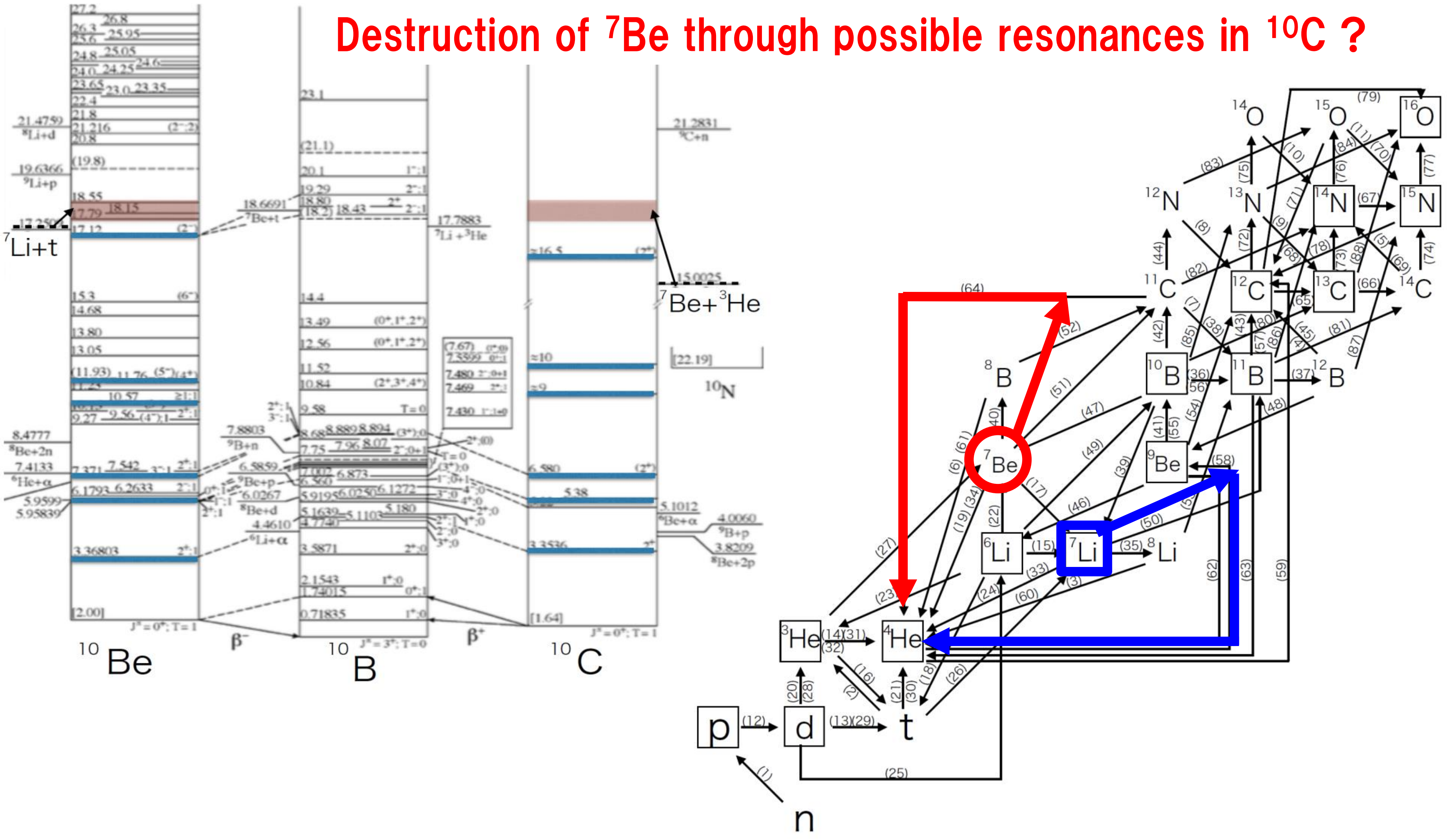
Gamow window

Big-Bang Nucleosynthesis (BBN) Theory stands on precise particle and nuclear physics!

$^7Li(^3H, 2n\alpha)\ ^4He$

$^7Be(^3He, 2p\alpha)\ ^4He$

Destruction of ^7Be through possible resonances in ^{10}C ?



Resonance in ^{7}Be (^{3}He,2pa) ^{4}He could not efficiently destroy ^{7}Be for kinematical conditions.

PHYSICAL REVIEW C **93**, 045804 (2016)

Low-lying resonances and relativistic screening in Big Bang nucleosynthesis

M. A. Famiano,[1,2,*] A. B. Balantekin,[2,3,†] and T. Kajino[2,4,‡]

$$\sigma(E) = \pi \bar{\lambda}^2 \omega\gamma \frac{\Gamma_{\text{total}}}{(E - E_R)^2 + \Gamma^2_{\text{total}}/4}, \qquad \gamma = \frac{\Gamma_{\text{in}}\Gamma_{\text{out}}}{\Gamma_{\text{total}}}$$

Theoretical Challenge

$$\Gamma_p(E) = 2P_L(E)\gamma_L(a)^2, \qquad \gamma_L^2(a) = \theta_L^2(a)\gamma_W^2(a) = \theta_L^2 \frac{3\hbar^2}{2m_{12}a^2}$$

$$P_L(a) = \frac{ka}{F_L^2(ka) + G_L^2(ka)} = \frac{\rho}{F_L^2(\eta,\rho) + G_L^2(\eta,\rho)},$$

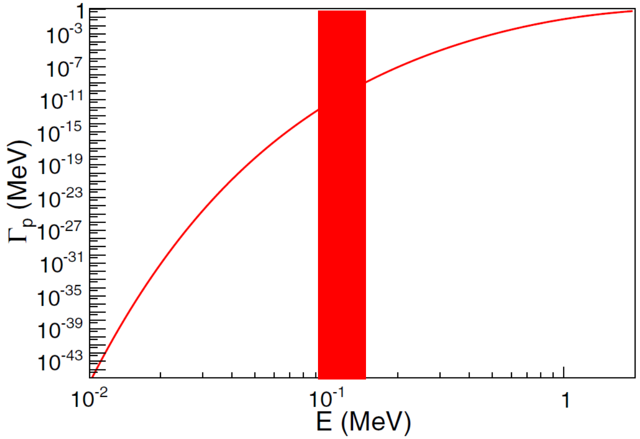


FIG. 7. The assumed entrance channel width as a function of incident particle energy for the ^{7}Be(^{3}He,γ)^{10}C reaction.

Integrand of <σv>

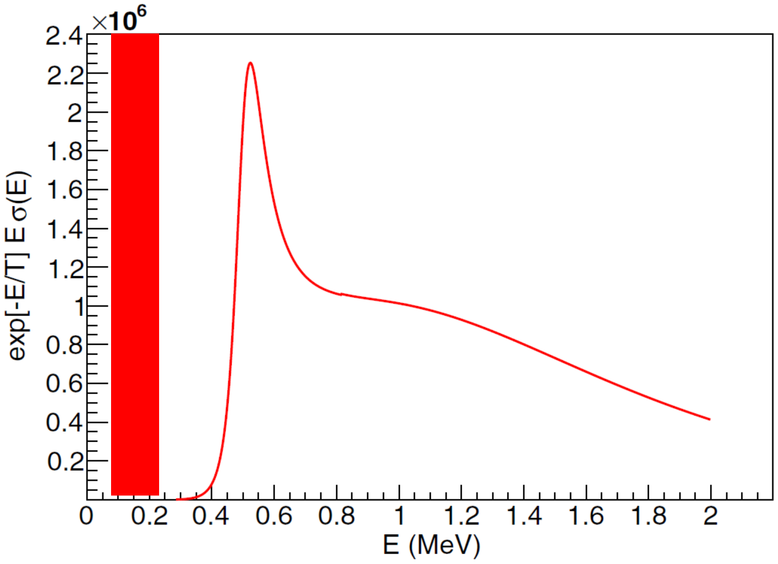
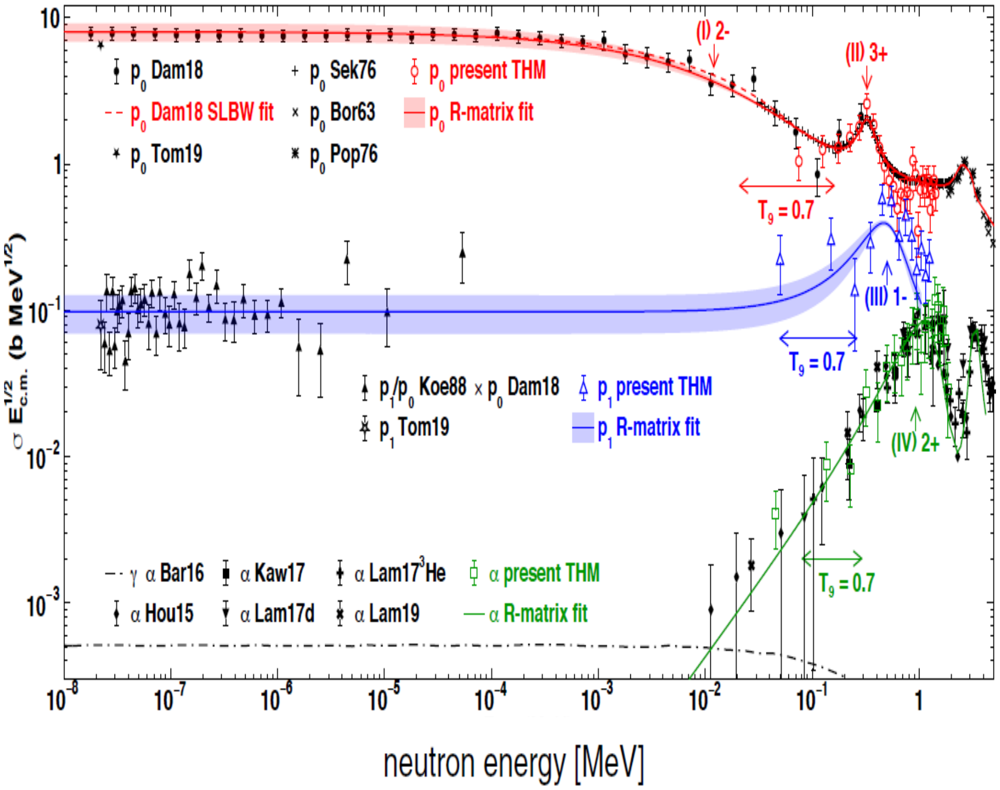


FIG. 8. The integrand of the thermonuclear reaction rate for the energy-dependent width of the ^{7}Be(^{3}He,γ)^{10}C reaction at $T = 1$ MeV for a resonance located at $E_R = 500$ keV.

^{7}Be(n, p)^{7}Li



Hayakawa, Yamaguchi + Catania (2021)
— Trojan Horse Method —

^{7}Be(n, p$_0$)^{7}Li + ^{7}Be(n, p$_1$)^{7}Li*

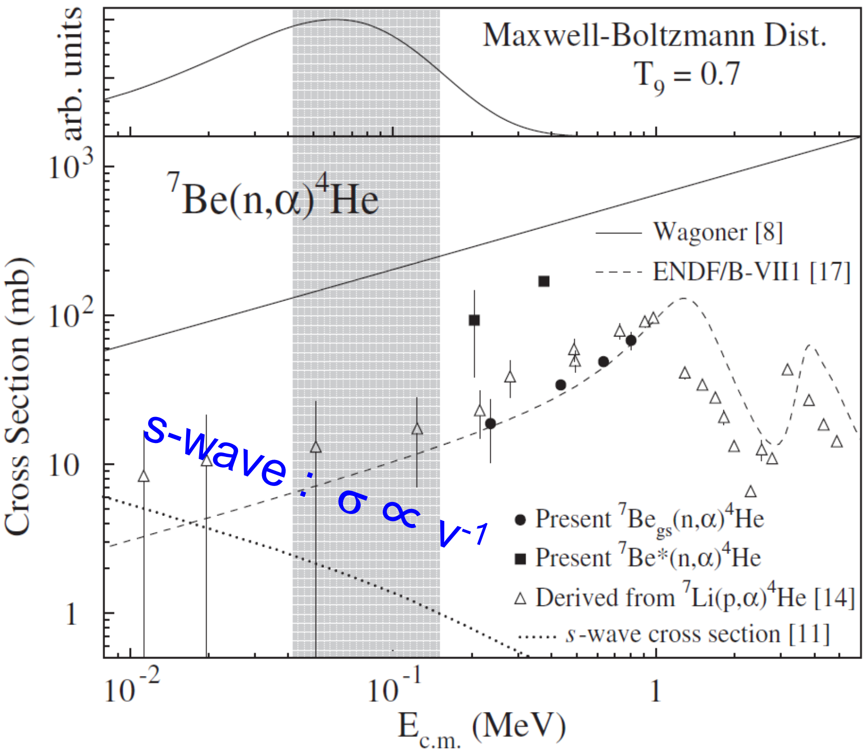
$\sigma^*(0.024\ \mathrm{eV}) / \sigma_{tot} = 1\%$

$\sigma^*(100\ \mathrm{keV}) / \sigma_{tot} < \boxed{15\%}$!

^{7}Be(n, α)^{4}He

Time-Reversal Measurement of the *p*-Wave Cross Sections of the ^{7}Be(*n*,*α*)^{4}He Reaction for the Cosmological Li Problem

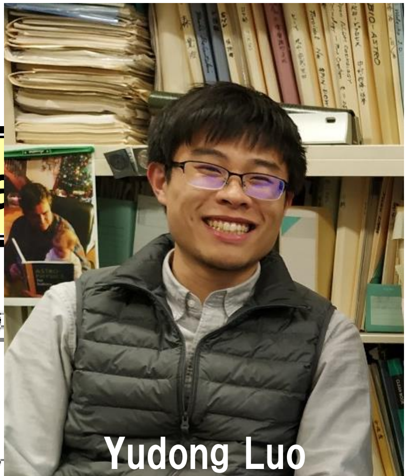
T. Kawabata et al., Phys. Rev. Lett. **118**, 052701 (2017).



s-wave : $\sigma \propto v^{-1}$

3. Cosmological solution ?

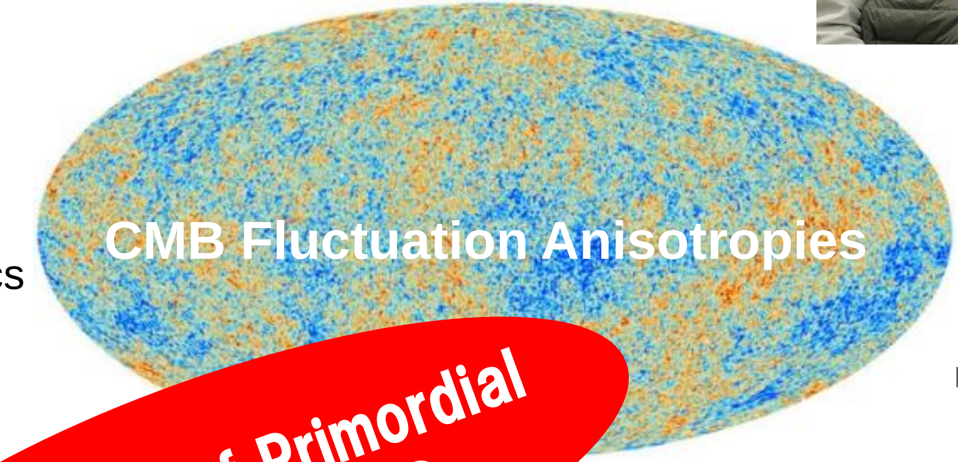
The Power of Quantum Mechanics and Rela


Yudong Luo

Quantum Systems of Particles and Nuclei

$$n_i(p)dp = \frac{1}{2\pi^2} g_i\ p^2 \left[\exp\left(\frac{E_i(p) - \mu_i}{kT}\right.\right.$$

- Elementary Particles; Relativistic
- Atomic Nuclei; Non-relativistic
- Fermi vs. Bose Statistics Planckian Maxwell-Boltzmann



Planck

Flucuations of Primordial Magnetic Field ?

Expansion Dynamic

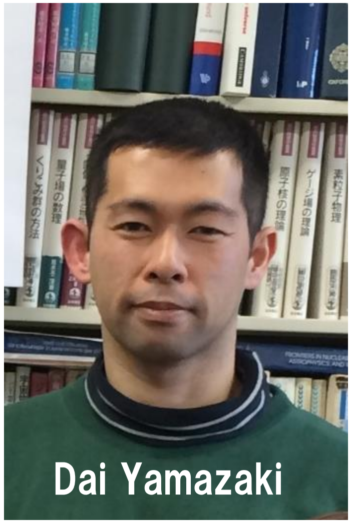
$$\frac{G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2}$$

- Einstein Eq.
- Fluid Dynamic: *umerical simulation for SNe etc.*

Reaction Network

$$dn_i/dt = \sum_{kl\,j} <\sigma_{kl\rightarrow ij}\,\upsilon> n_k\, n_l\ - \sum_{j\,kl} <\sigma_{ij\rightarrow kl}\,\upsilon> n_i\, n_j\ - n_i/\tau_i$$

- Nuclear (strong), Electro-magnetic, and Weak interactions



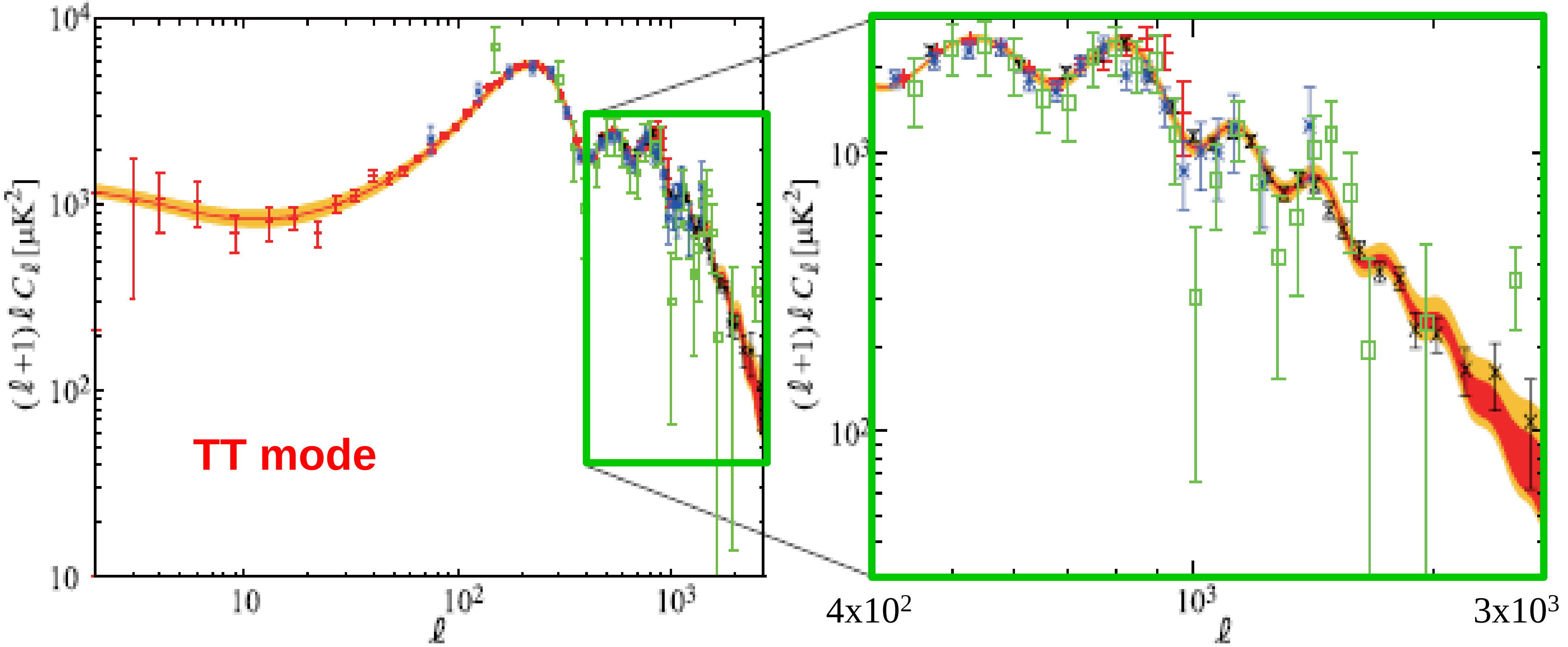
“Primordial Magnetic Field” and “ν mass” in CMB

Yamazaki, Kajino, Mathews & Ichiki, PR D81 (2010), 023008; ApJ 825 (2006), L1; PRD, 77, 043005 (2008); PR D81 (2010), 103519; Phys. Rep. 517 (2012), 141.

B_λ < 2nG (2σ), **$\sum m_\nu$ < 0.2 eV (2σ)**

Integrated Sachs-Wolfe Effect, similarly to CDM

Free Streaming Effect of Massive Neutrinos



Basic Equations for Cosmic Metric Perturbation

Isotropic & Homogeneous BG

$$\left(\frac{a'}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

Friedmann Eq.

$$k\frac{1}{a^2}\frac{a'}{a}\mathcal{Z} = 4\pi G\delta\rho + k^2\frac{H_T}{a^2}$$

Linear Metric Perturbation

Perturbed Einstein Equation of "Super-Horizon Scale (kτ<<1)"

$$\boxed{\ddot{H}_T} + 2\frac{\dot{a}}{a}\dot{H}_T = 8\pi G a^2 (p_\nu \boxed{\pi_\nu} + p_\gamma \boxed{\pi_{ext}})$$

Metric perturbation

ν-anisotropic stress

Extra anisotropic stress due to **Megnetic Field**

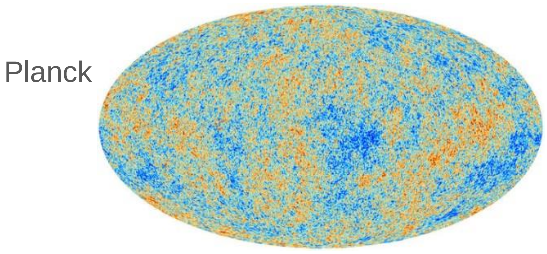
Effective wave number
for finite neutrino mass

$$k_{\rm eff}^2 = k^2 + k_{\rm m}^2$$

$$k_{\rm m} = \sqrt{\frac{1}{2}\frac{5}{7\pi^2}H_0^2\Omega_R\frac{4R_\nu + 15}{c}\boxed{m_\nu^2}}$$

Neutrino
mass

Primordial Magnetic Field (PMF) Fluctuations induce T-fluctuation.



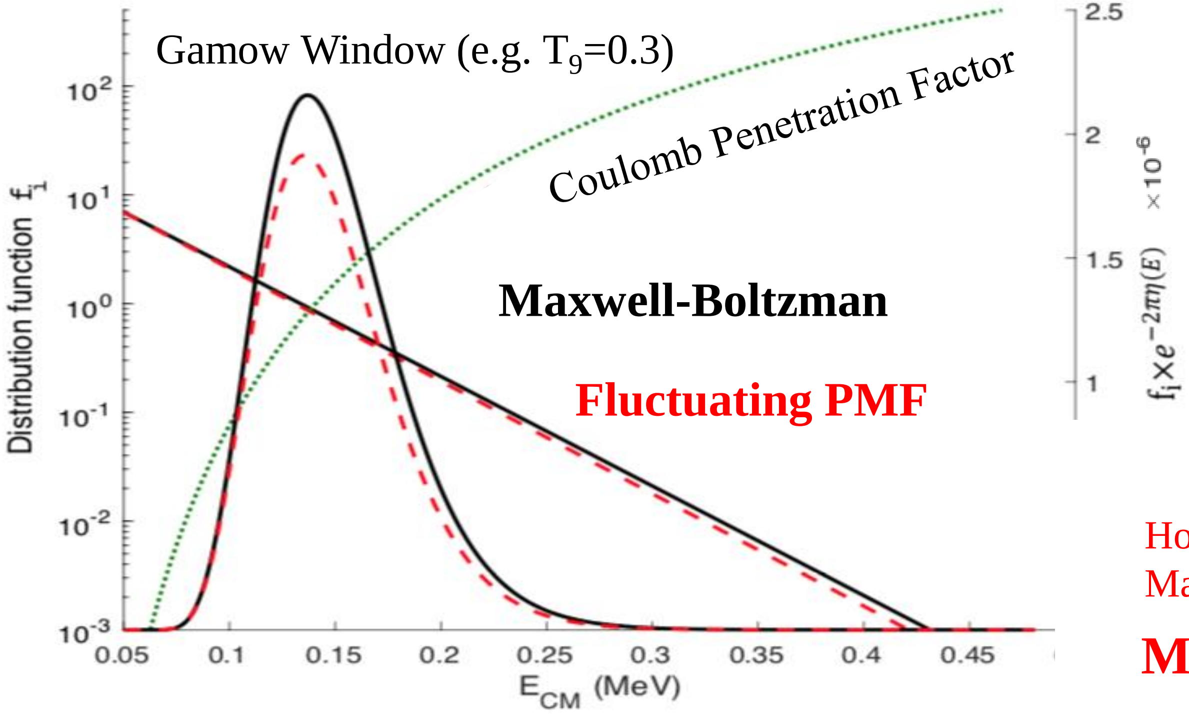
$$\rho_\lambda = \frac{\langle B^2\rangle}{8\pi} = \frac{1}{8\pi}\int_{k_{[min]}}^{k_{[max]}} \frac{dk}{k}\frac{k^3}{2\pi^2}P_{[PMF]}(k)$$

$$B^2 \propto P_{[PMF]} = Ak^{n_B}$$ *CMB power law spectrum*

Thermonuclear Reaction Rate: $\langle\sigma\nu\rangle(T) = \left(\frac{\mu}{2\pi kT}\right)^{3/2}\int_0^\infty v\cdot\sigma(v)\cdot\underline{P(v)}\cdot 4\pi v^2 dv$

$$f(\beta) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(\frac{\pi g}{30}\cdot(T_{eff}^4-\beta^{-4})-\rho_\lambda)^2}{2\sigma^2}\right]\cdot\frac{2\pi g}{15}\beta^{-5}$$

$$\boxed{P(v) = \int d\beta p(v|\beta)f(\beta)}$$



Temp. Fluctuation
→ various T=β⁻¹

Yamazaki, Kajino, Mathews, Ichiki
Phys. Rep. 517 (2012), 141.

Luo, Kajino, Kusakabe, Mathews,
ApJ. 872 (2019), 172 (9pp).

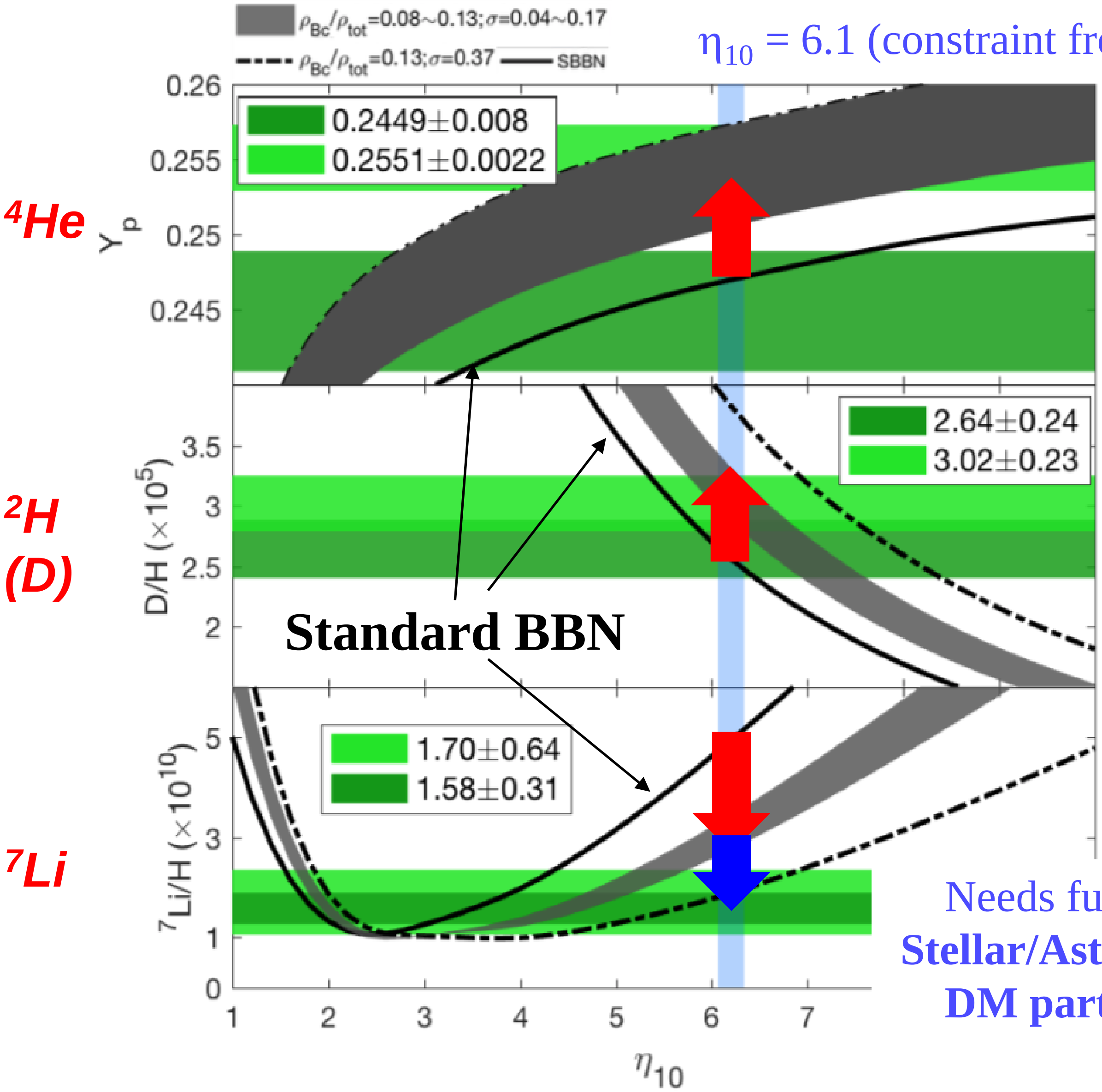
"Tsallis Distrib. (1<q)"

Hou, He, Parikh, Kahl, Bertulani, Kajino,
Mathews & Zhao, ApJ. 834 (2017), 165.

Mechanism, UNKNOWN ?

Fluctuating PMF: Non-MB distribution for BBN

Y.-D. Luo, T. Kajino, M. Kusakabe, and G. J. Mathews, ApJ. **872** (2019), 172;
PRL (2020), to be submitted.



Additional PMF accelerates cosmic expansion rate:

→ higher n/p ratio

→ higher ^4He

Destruction, quenched:

$^2H+^2H \rightarrow p+^3H$

$\rightarrow n+^3He$

Production, quenched:

$^4He+^3He \rightarrow {}^7Be+\gamma$

Needs further decrease of ^7Be for:

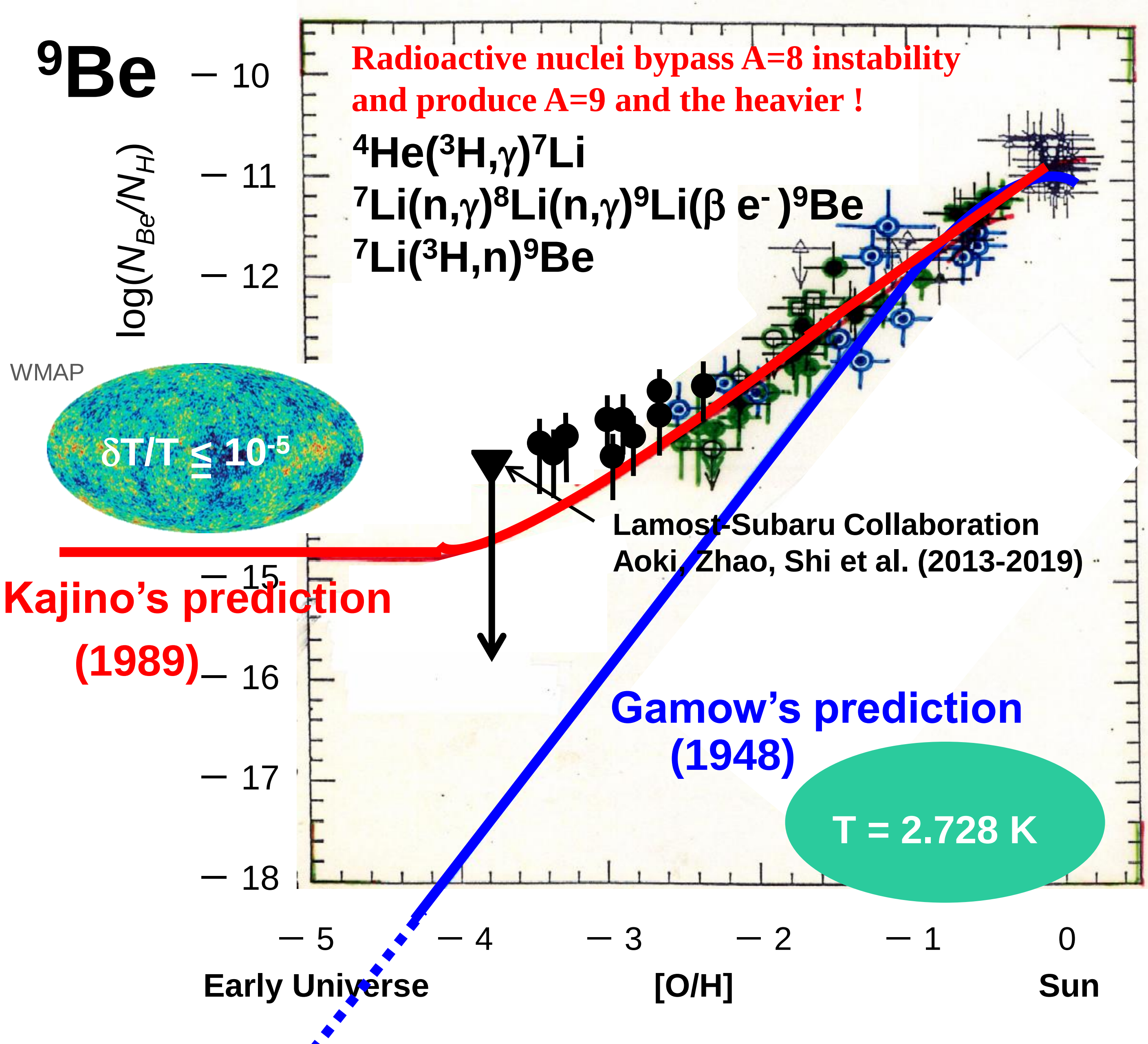
Stellar/Astration Effect, PMF dissipation, DM particle decay, or Nucl. React.

Gamow’s BBN Model

Alpher, Bethe & Gamow, PR 73 (1948), 803.

Kajino’s Fluctuation BBN Model

Kajino and Boyd, ApJ 359 (1989, 1990) 267.



Radioactive nuclei bypass A=8 instability and produce A=9 and the heavier !

$^{4}He(^{3}H,\gamma)^{7}Li$

$^{7}Li(n,\gamma)^{8}Li(n,\gamma)^{9}Li(\beta\ e^{-})^{9}Be$

$^{7}Li(^{3}H,n)^{9}Be$

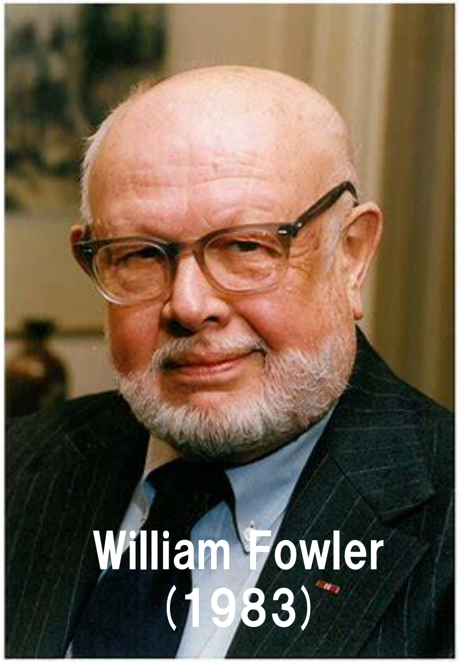
Smoot & Mather discovered CMB fluctuation in 1992.

Content

1. Big-Bang Cosmology

2. Supernova and Merger

3. ν -Oscillation

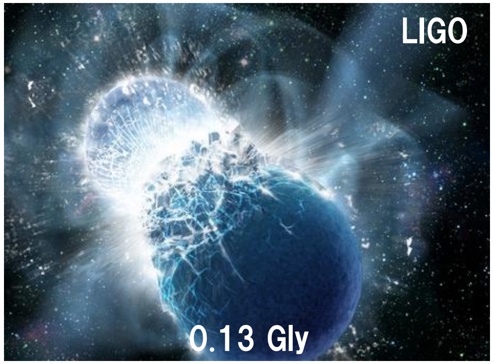

William Fowler
(1983)


Kip Thorn
(2017)

GW170817

Abbott et al. (LIGO-Virgo), PRL 119 (2017), 16101.

1. GW170817 (LIGO-Virgo) : $0.86<M/M_{\odot}<2.26$ → EoS
2. GRB170817A (Fermi-GBM) : 1.7 s
3. No ν–Signal: 10^{-6} weaker than SN1987A (0.16 Mly)
4. X-rays & Radio waves
5. **Optical and Near-infrared**



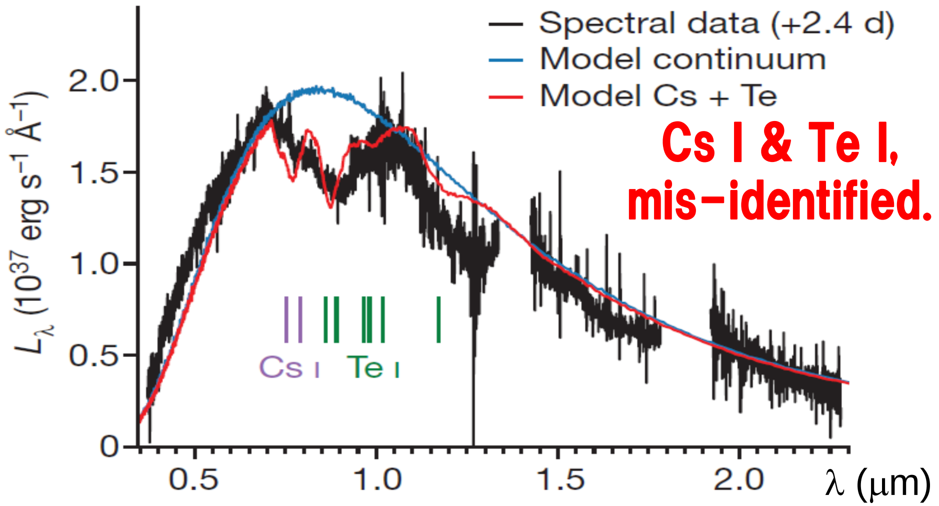
Article Nature | Vol 574 | 24 OCTOBER 2019 | **497**

Identification of strontium in the merger of two neutron stars

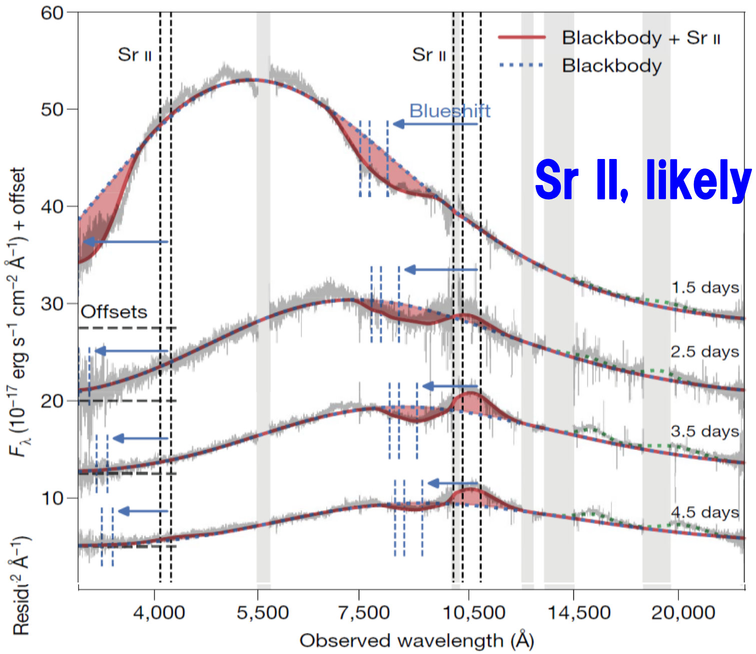
Darach Watson[1,2*], Camilla J. Hansen[1,3,20], Jonatan Selsing[1,2,20], Andreas Koch[4], Daniele B. Malesani[1,2,5], Anja C. Andersen[1], Johan P. U. Fynbo[1,2], Almudena Arcones[6,7], Andreas Bauswein[7,8], Stefano Covino[9], Aniello Grado[10], Kasper E. Heintz[1,2,11], Leslie Hunt[12], Chryssa Kouveliotou[13,14], Giorgos Leloudas[1,5], Andrew J. Levan[15,16], Paolo Mazzali[17,18] & Elena Pian[19]

Lanthanoids (r-elements), discovered ?

Smartt et al., Nature, 551, 75 (2017)



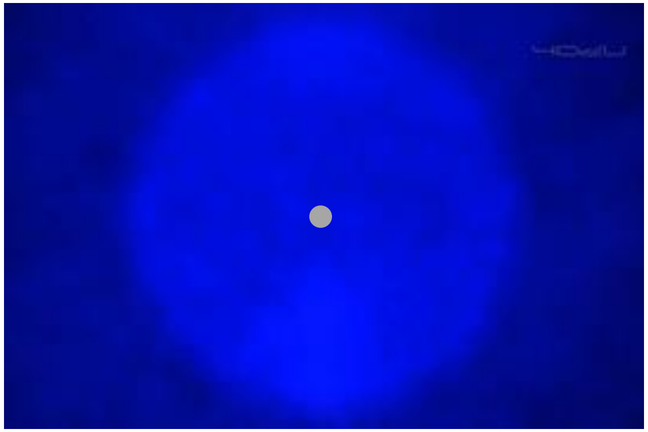
Cs I & Te I, mis-identified.



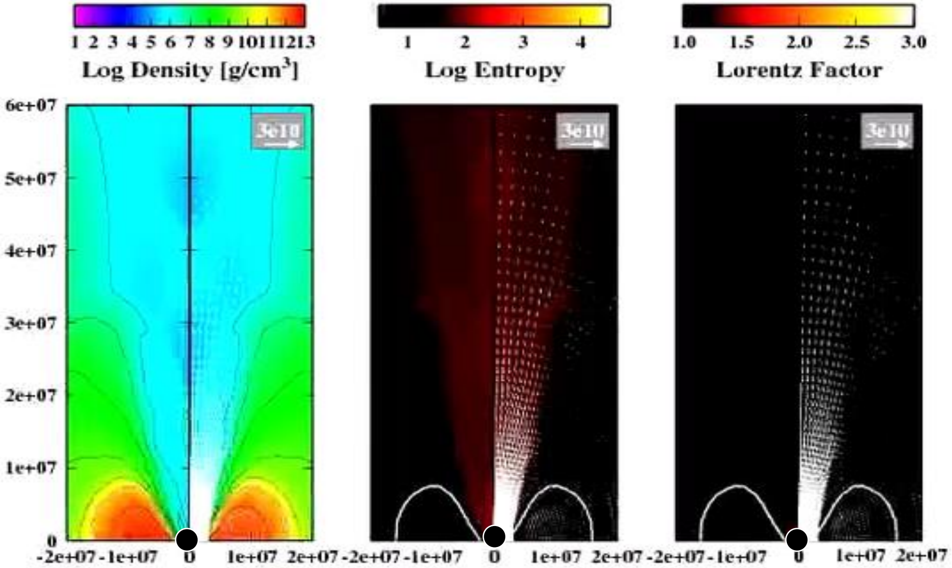
Sr II, likely !

Core Collapse and Explosion of SINGLE Massive Star

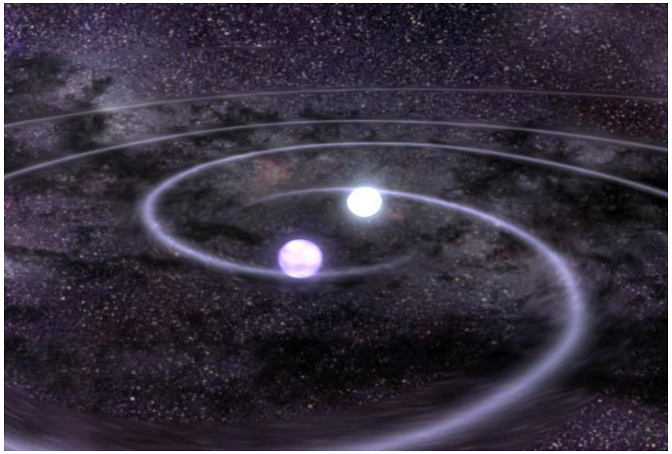
Supernova: ν-Wind & MHD Jet
(Neutron Star)



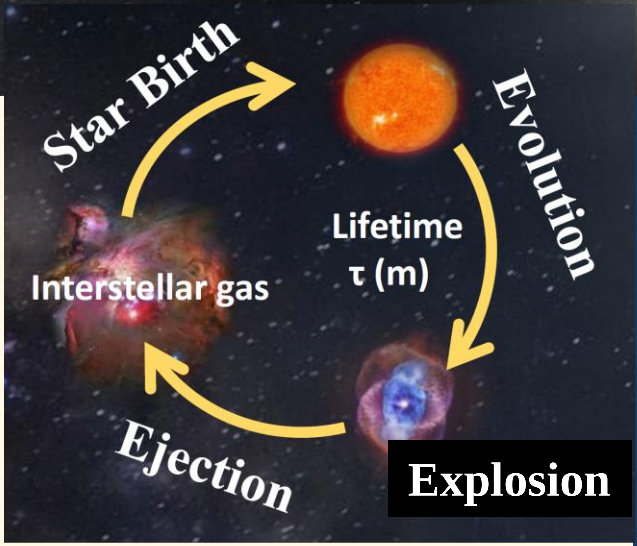
Collapsar (Black Hole)



BINARY Neutron Star Merger



Cosmic & Galactic Evolution



Cosmic Gas- and Nuclear-Evolution

$$\dot{\sigma}_X = Inflow \cdot \delta_{X,gas} - \frac{\sigma_X}{\sigma_{gas}} \cdot \underline{B(\xi_{gas})} + \int \underline{B(t-\tau(m))\,\phi(m)\,E_X(m)}\,dm$$

Stellar Birth Rate

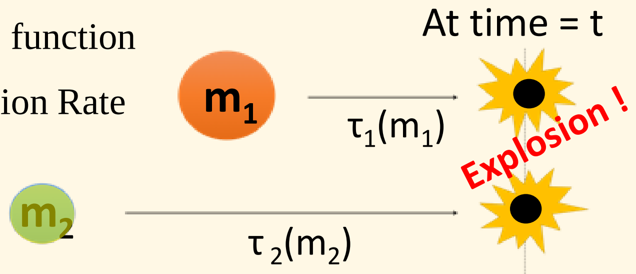
X = Ejected Nucleus from SNe or NSM

Supernova and Collapsar Rate :

$$R_{SNII} = \int_{m_l}^{m_h} \phi(m)\,B(t-\tau(m))\,dm$$

$\Phi(m)$: Initial mass function

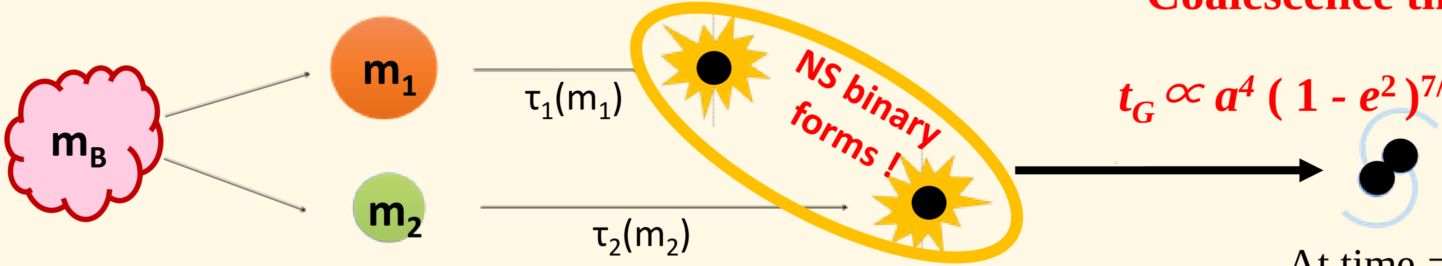
$B(t)$: Star Formation Rate



Neutron Star Merger Rate :

$$R_{NSM} = \epsilon_{NSM} \int_{m_l}^{m_h} dM_B\,\phi(M_B) \int_{q_l}^{1} dq\,f(q) \int_{a_l}^{a_h} da\,P(a)\,B(t-\tau(m_2)-t_G)$$

Coalescence time delay



$t_G \propto a^4 (1 - e^2)^{7/2} = ?$

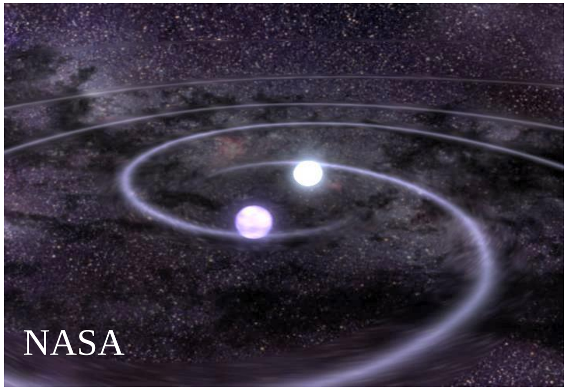
At time = t

q = m_2/m_1

a = separation of NS-binary

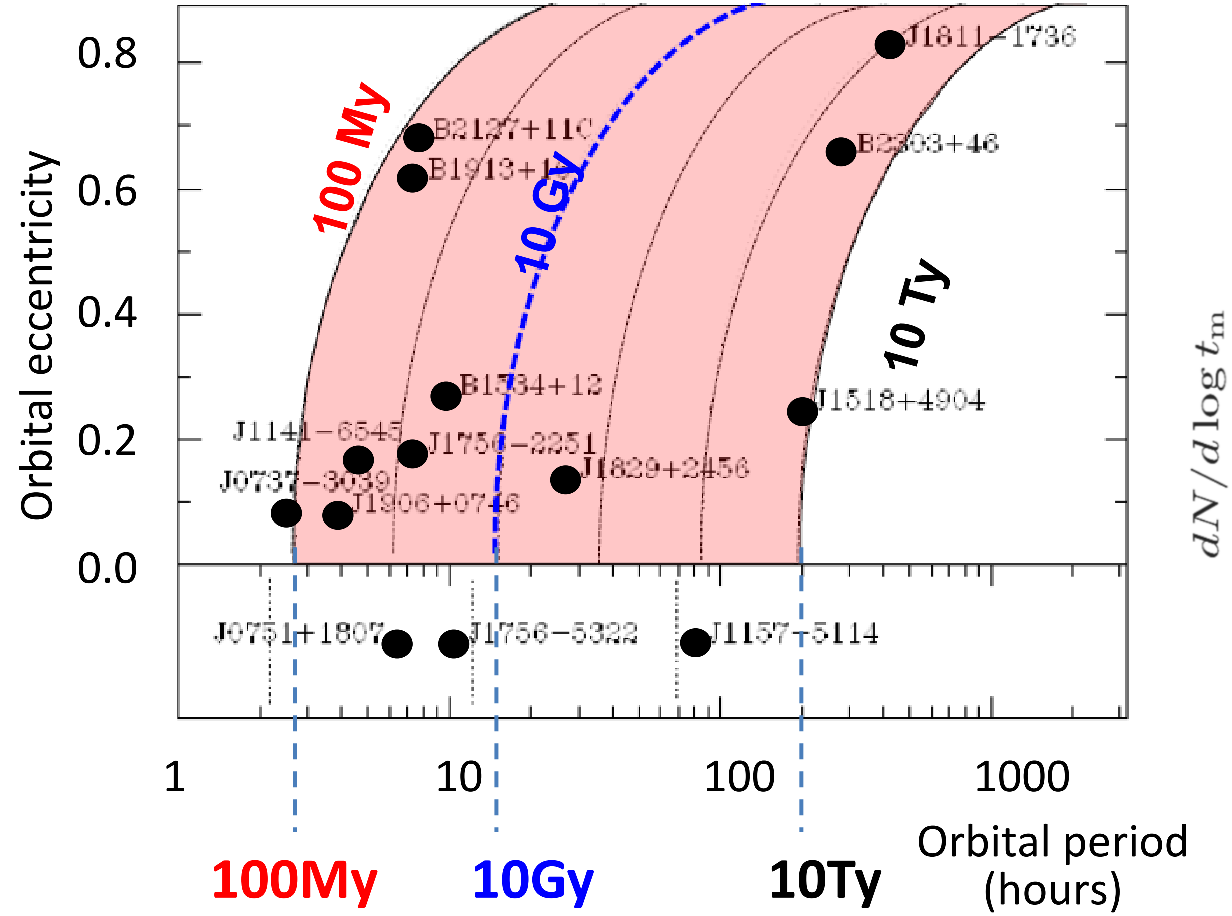
Merger Time Delay Problem

$$\tau_c \simeq 9.83 \times 10^6 \text{ yr} \left(\frac{P_b}{\text{hr}}\right)^{8/3} \text{x} \left(\frac{m_1 + m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1 - e^2)^{7/2}$$

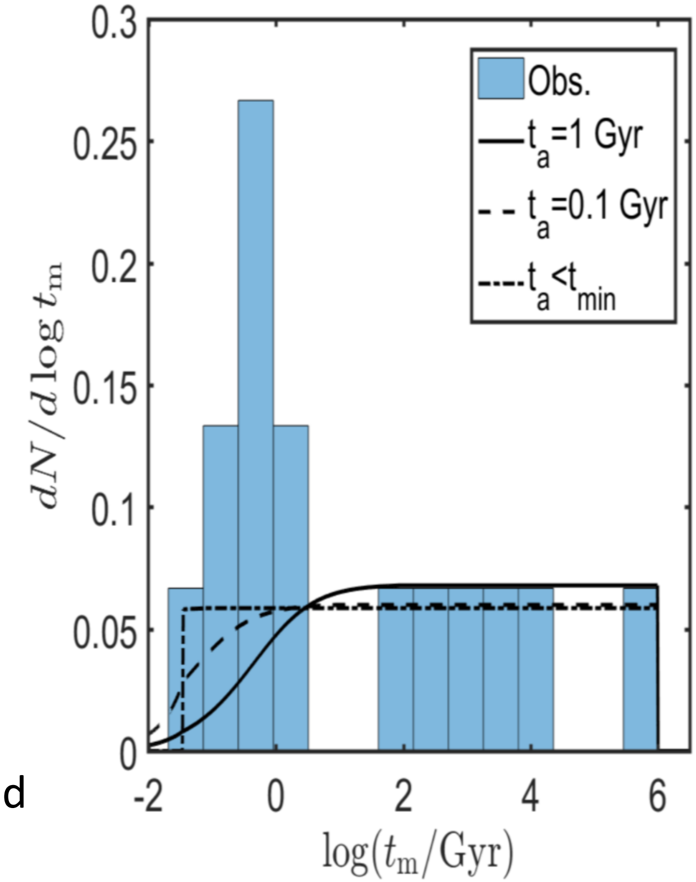


NASA

BINARY PULSARS : Lorimer, Living Rev. Rel. 11(2008), 8.

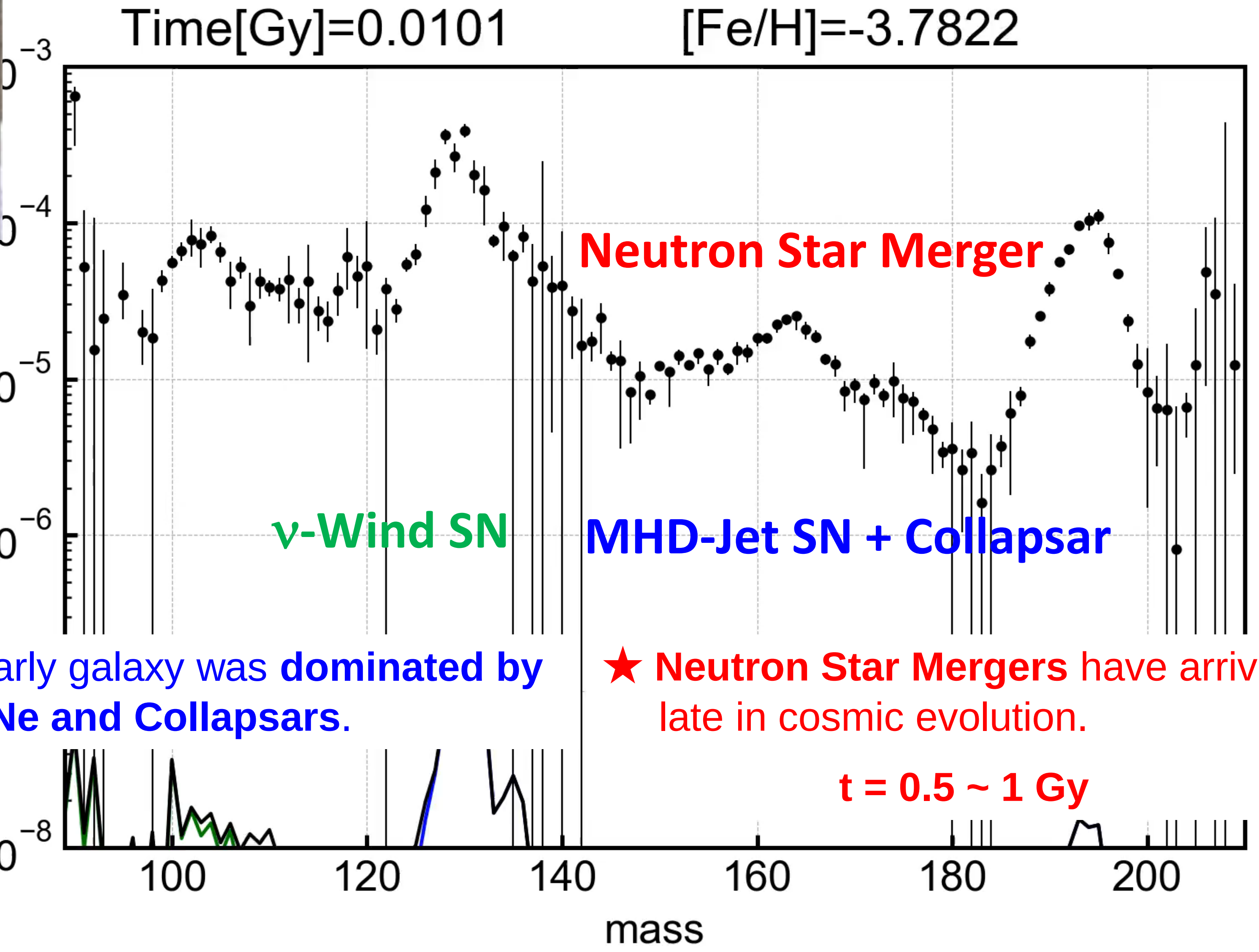


Beniamini+ (2019)



Cosmic Evolution of r-Process Abundance

Yamazaki, Kajino, Mathews, Tang, Shi, Famiano, (2021).

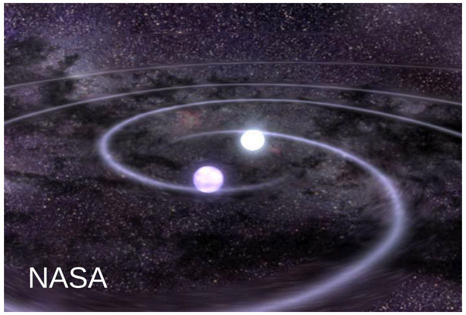


★ Early galaxy was **dominated by SNe and Collapsars.**

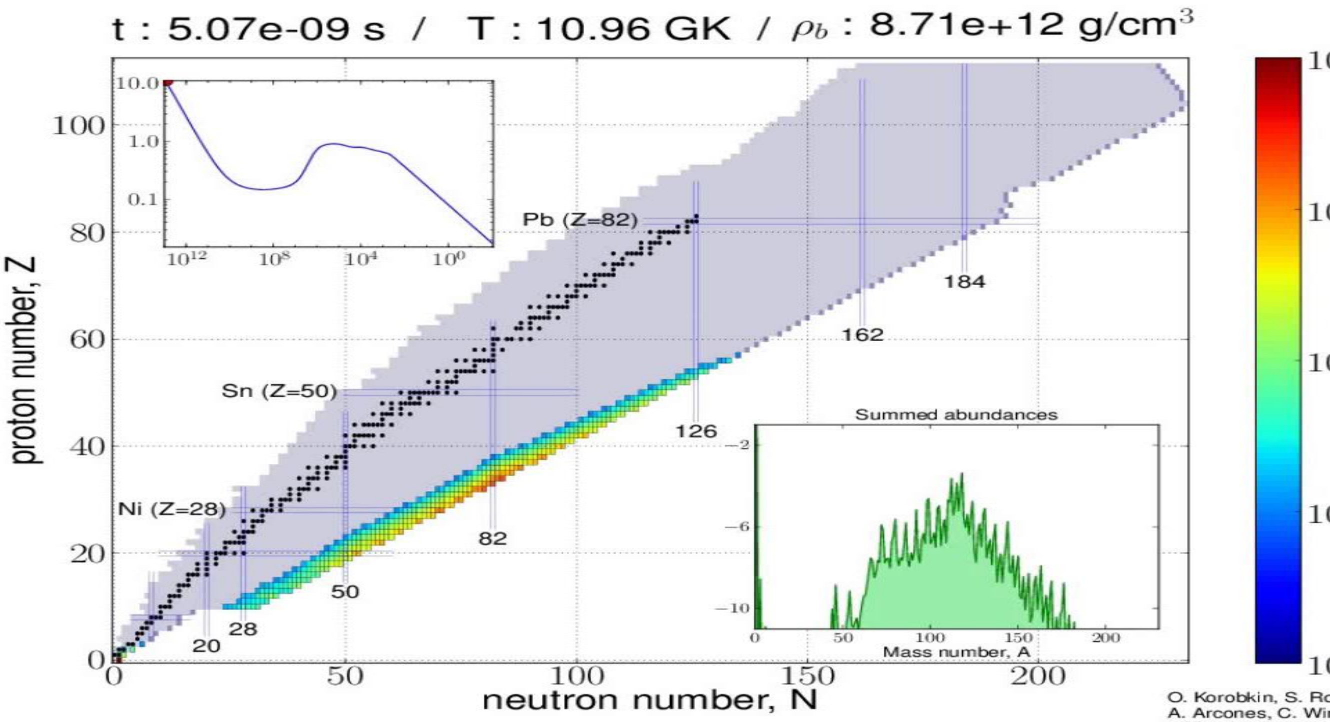
★ **Neutron Star Mergers** have arrived late in cosmic evolution.

t = 0.5 ~ 1 Gy

Neutron Star Merger

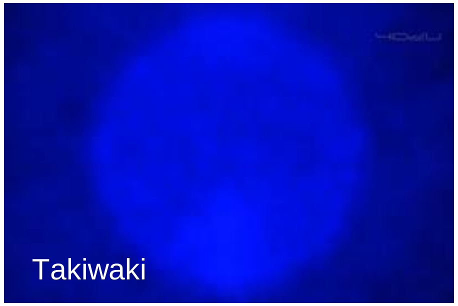


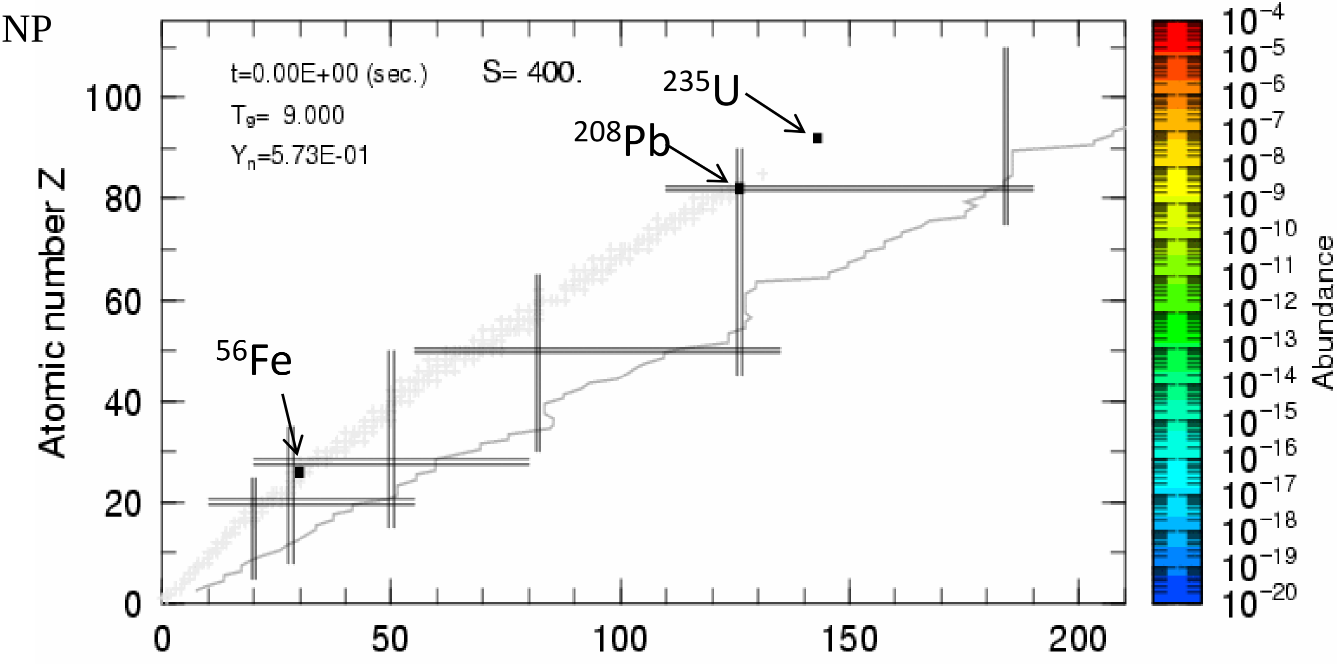
Shibagaki, Kajino, et al. (2016), ApJ 816, 79; Kajino & Mathews (2017), ROPP 80, 084901; Kajino, Aoki, Balantekin, Dihel, Famiano, Mathews (2019), PPNP 107, 109.



O. Korobkin, S. Ro
A. Arcones, C. Wi
arXiv:1206.2379

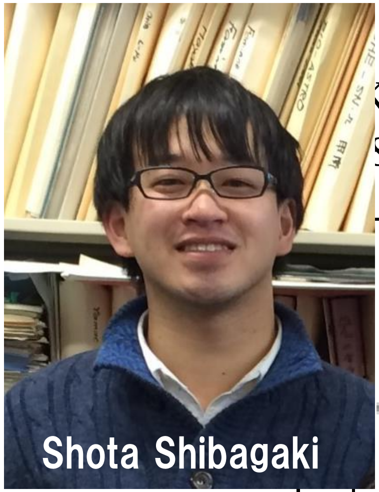
Supernova (MHD Jet)





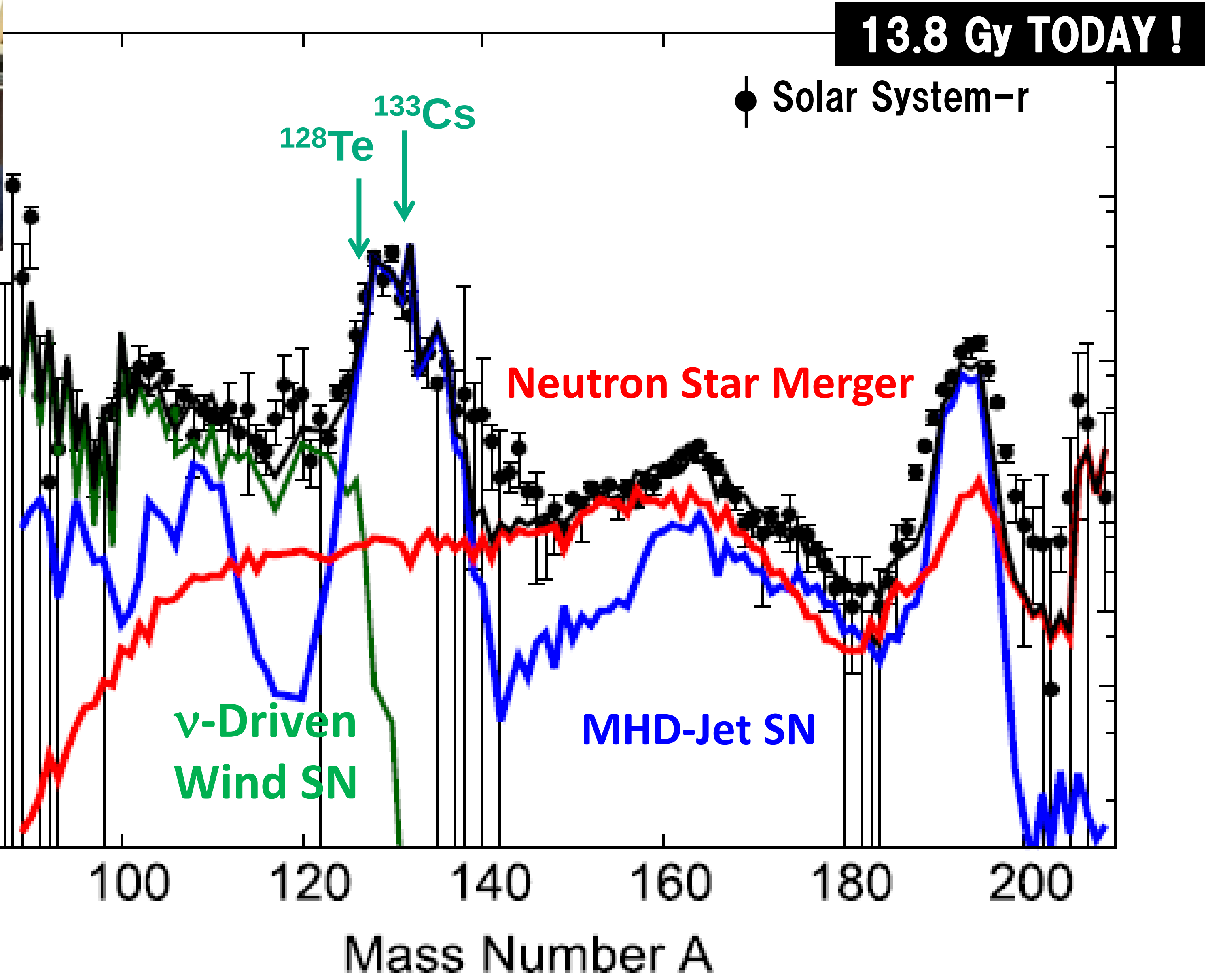
Solar System r-Process Abundance

Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2018);
& Mathews (2017), ROPP 80 , 084901; Kajino et al., PPNP 107 (2019) 109.

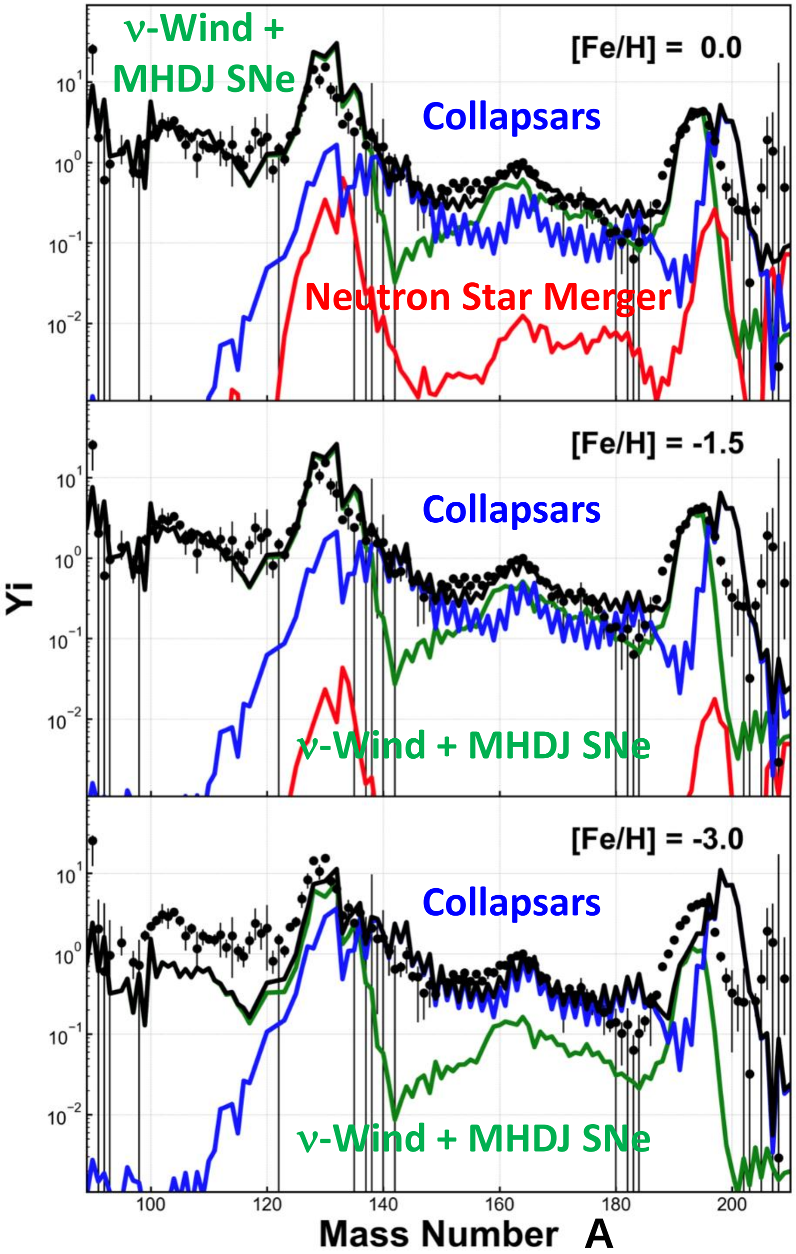


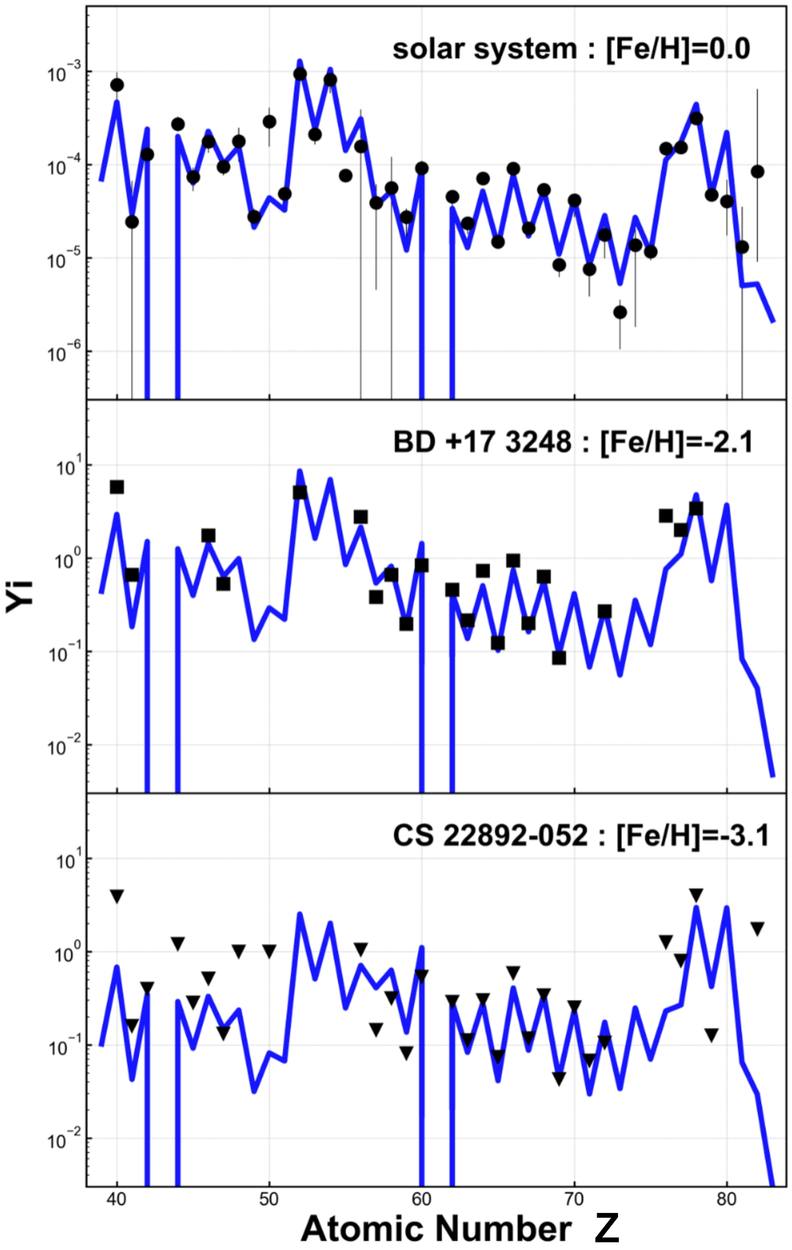
Shota Shibagaki

13.8 Gy TODAY !

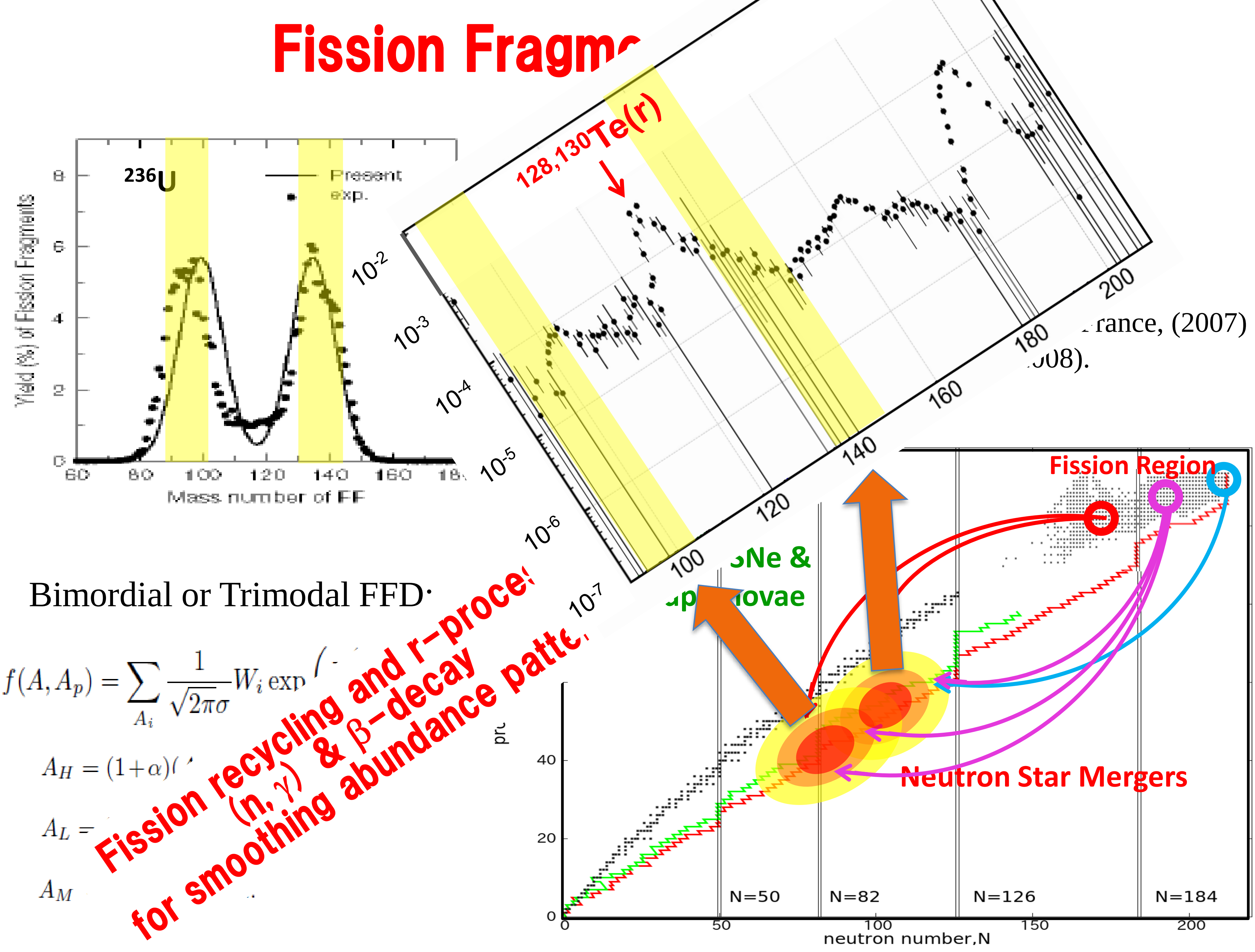


Yamazaki, Kajino, Mathews, Tang, Shi, Famiano, (2021).





Fission Fragm



rance, (2007)

008).

Bimordial or Trimodal FFD:

$$f(A, A_p) = \sum_{A_i} \frac{1}{\sqrt{2\pi\sigma}} W_i \exp ($$

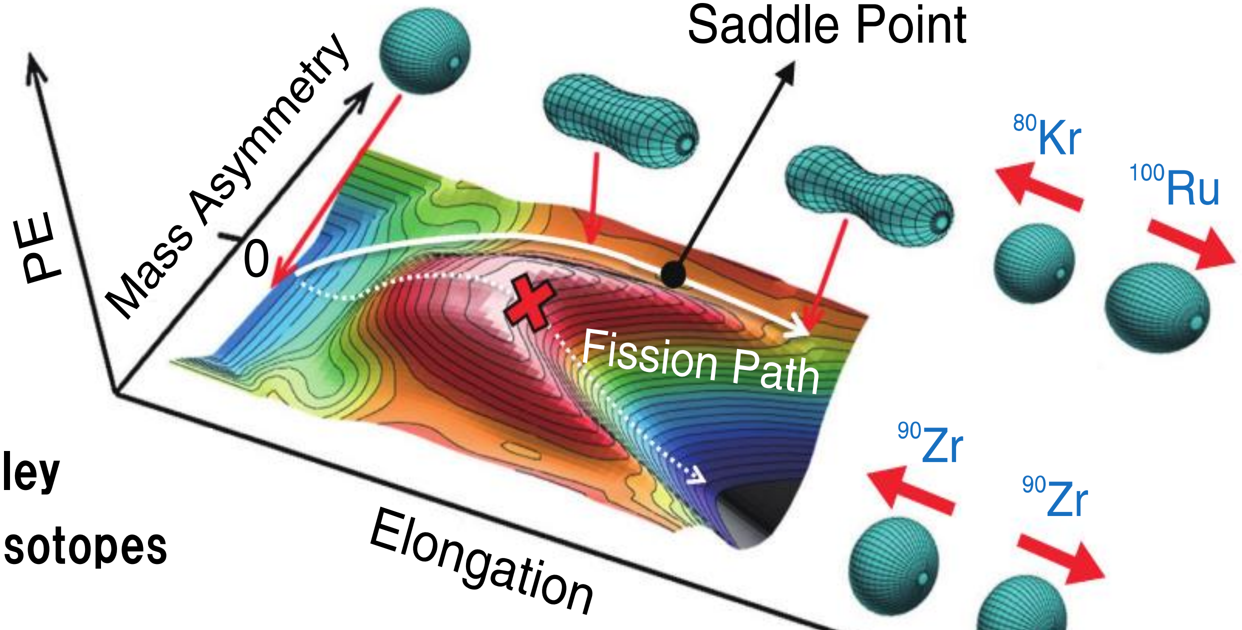
$$A_H = (1+\alpha)($$

$$A_L =$$

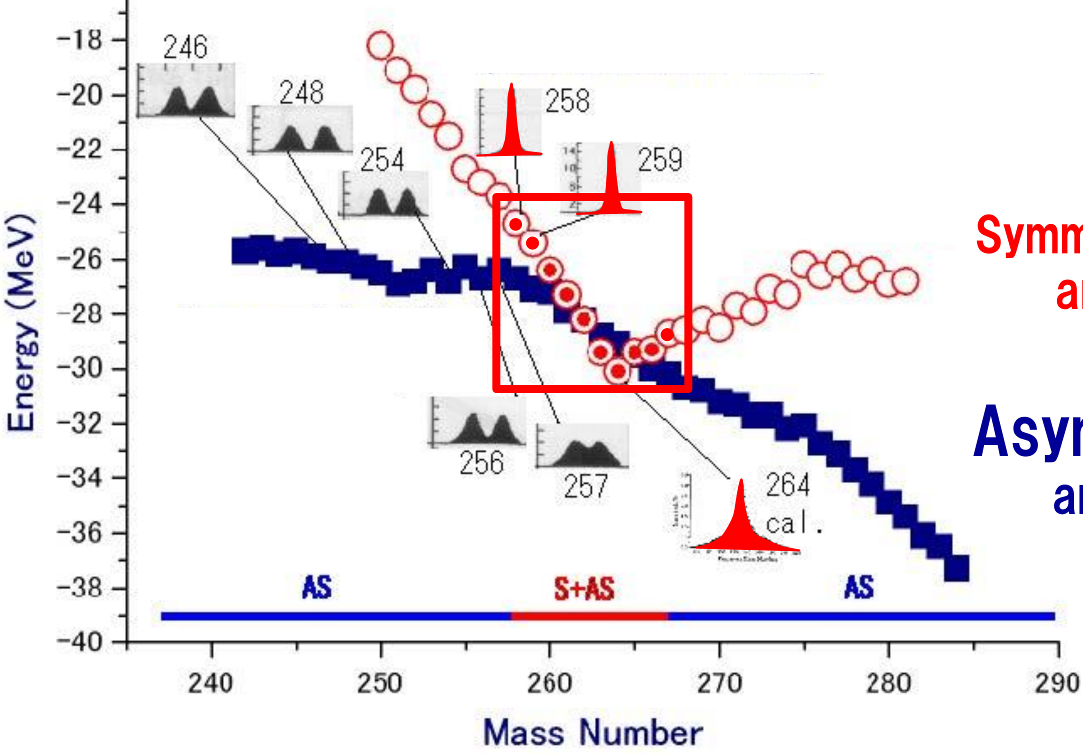
$$A_M$$

Fission recycling and r-proce
(n, γ) & β-decay
for smoothing abundance patte

Fission Path of Mercury



Potential Depth of Fission Valley (near Scission Point) of Fm isotopes

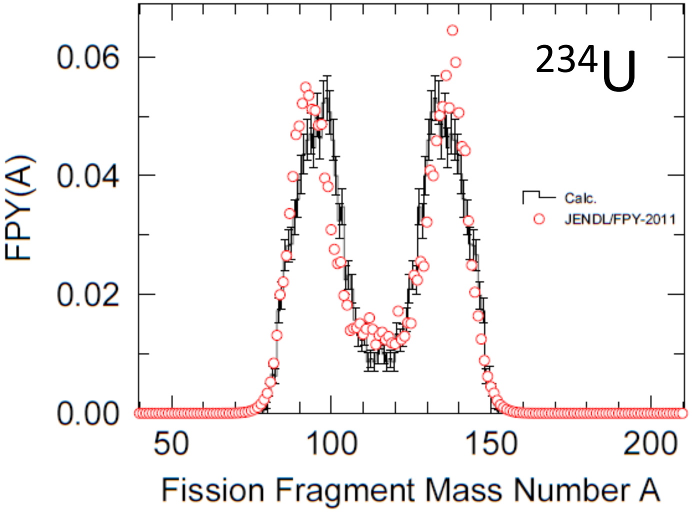


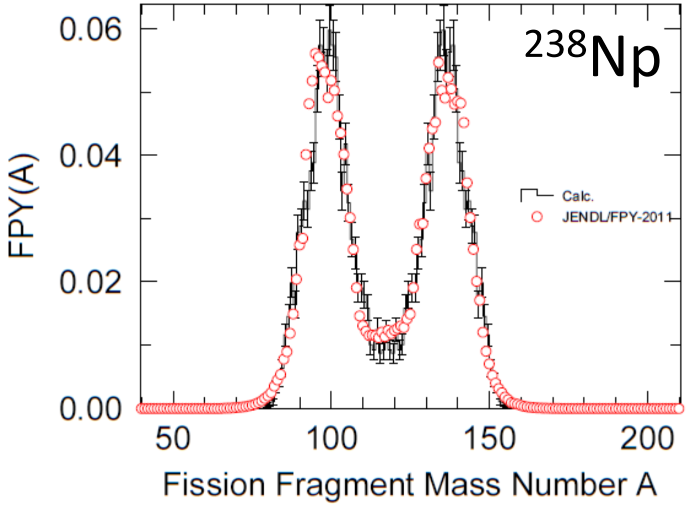
Symmetric Valley
around α=0, δ=0.05

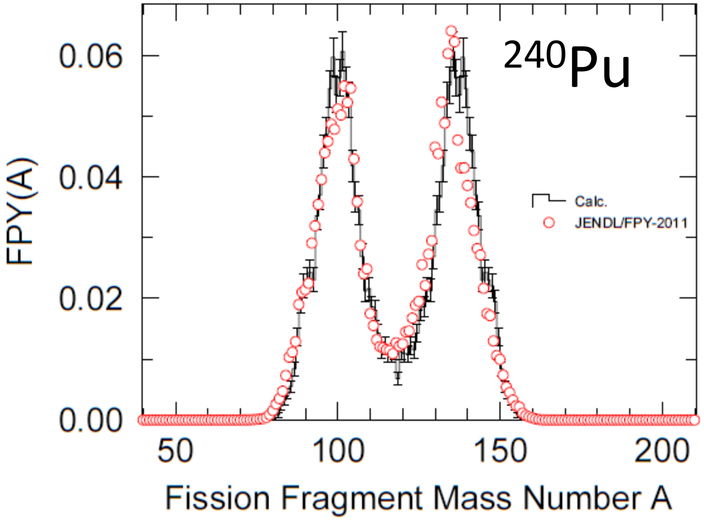
Asymmetric Valley
around α=0.15, δ=0.2

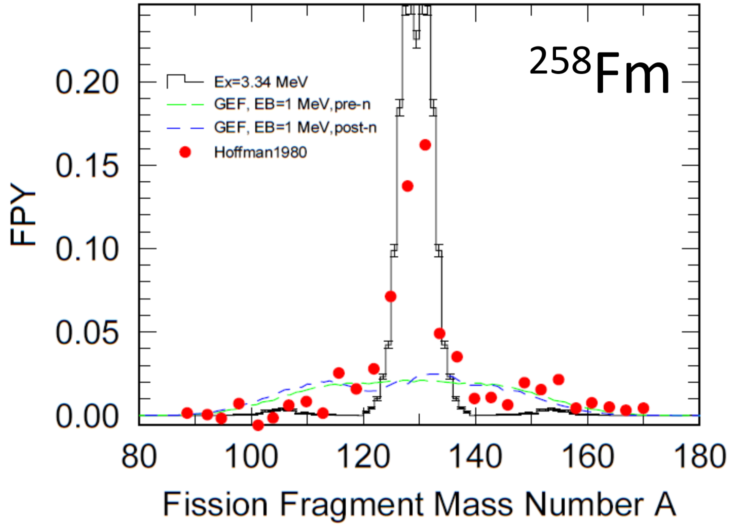
Mass Distribution of Fission Fragments at Ex=20MeV

Ishizuka et al., Phys. Rev. C96 (2017), 064616; Ivanyuk et al., Phys. Rev. C97, 054331 (2018);
Okumura et al., J. Nucl. Sci. Tech. 55, 1009 (2018); Usang et al., Sci. Reports, 9, 1525(2019)



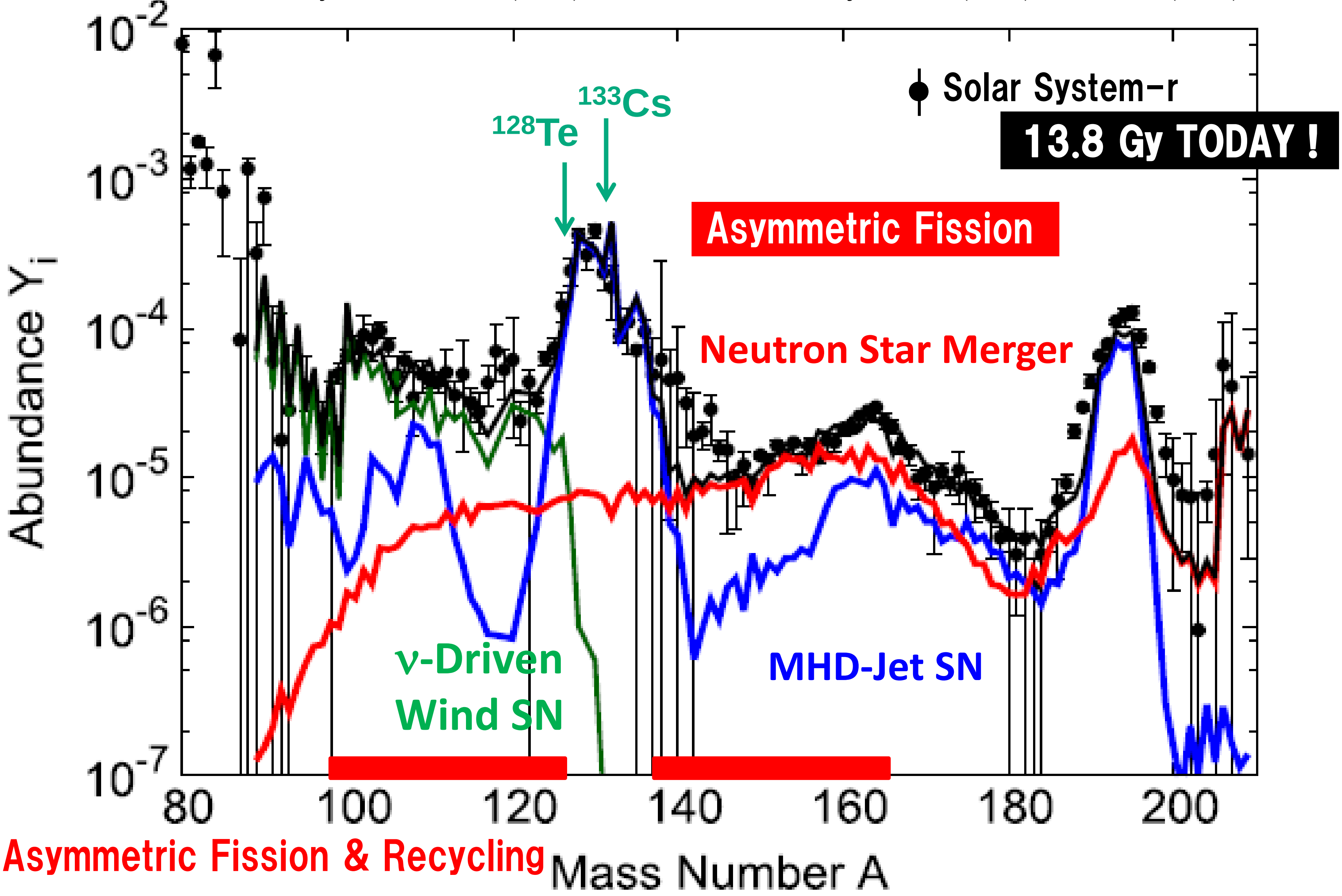






Present Day Solar System r-Process Abundance

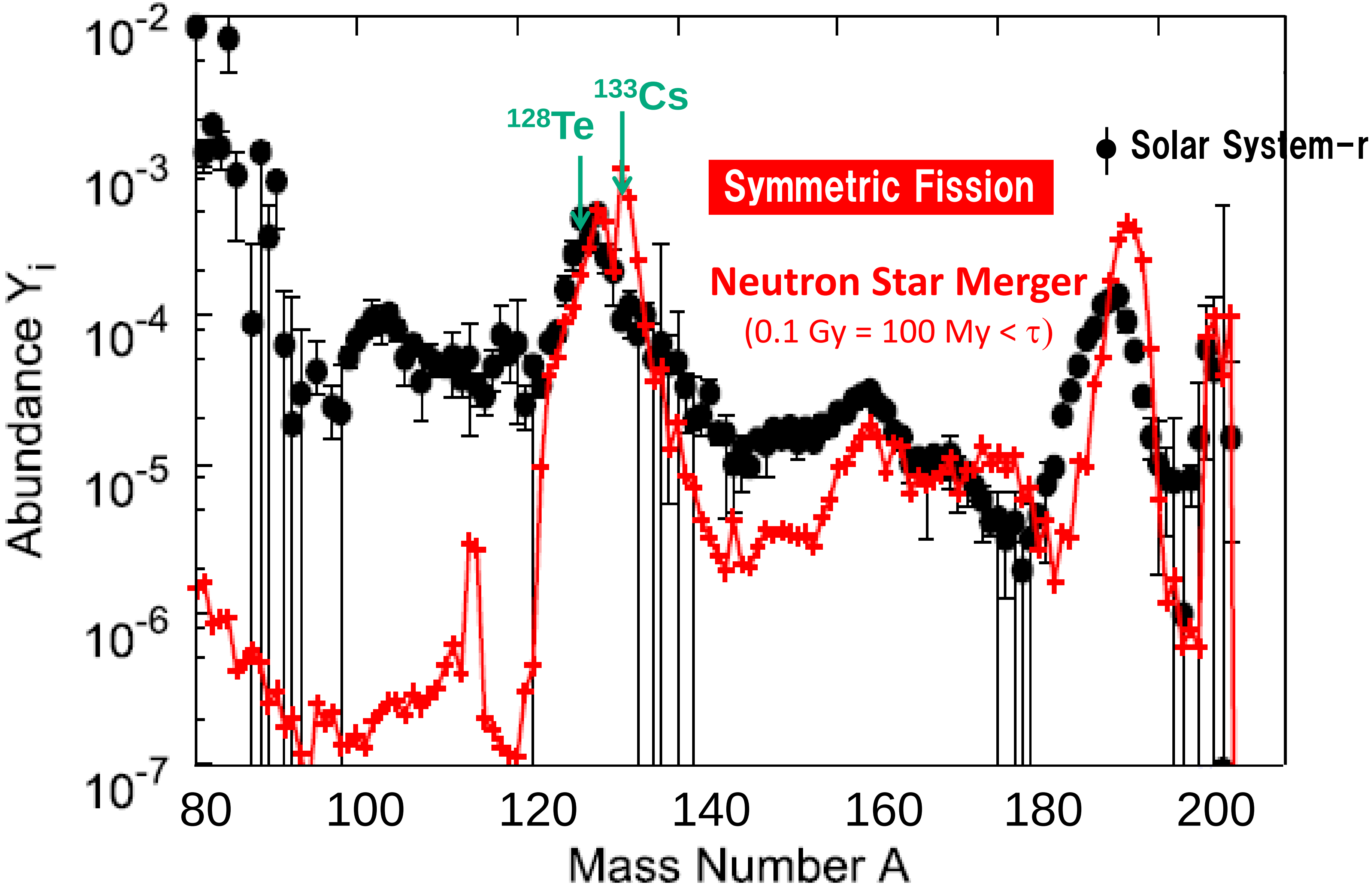
Shibagaki, Kajino, Chiba, Mathews, Nishimura & Lorusso (2016), ApJ 816, 79; ApJ (2018);
Kajino & Mathews (2017), ROPP 80 , 084901; Kajino et al. (2019), PPNP 107 (2019) 109.



Neutron Star Merger, dep.t on Fission & Mass Formula !

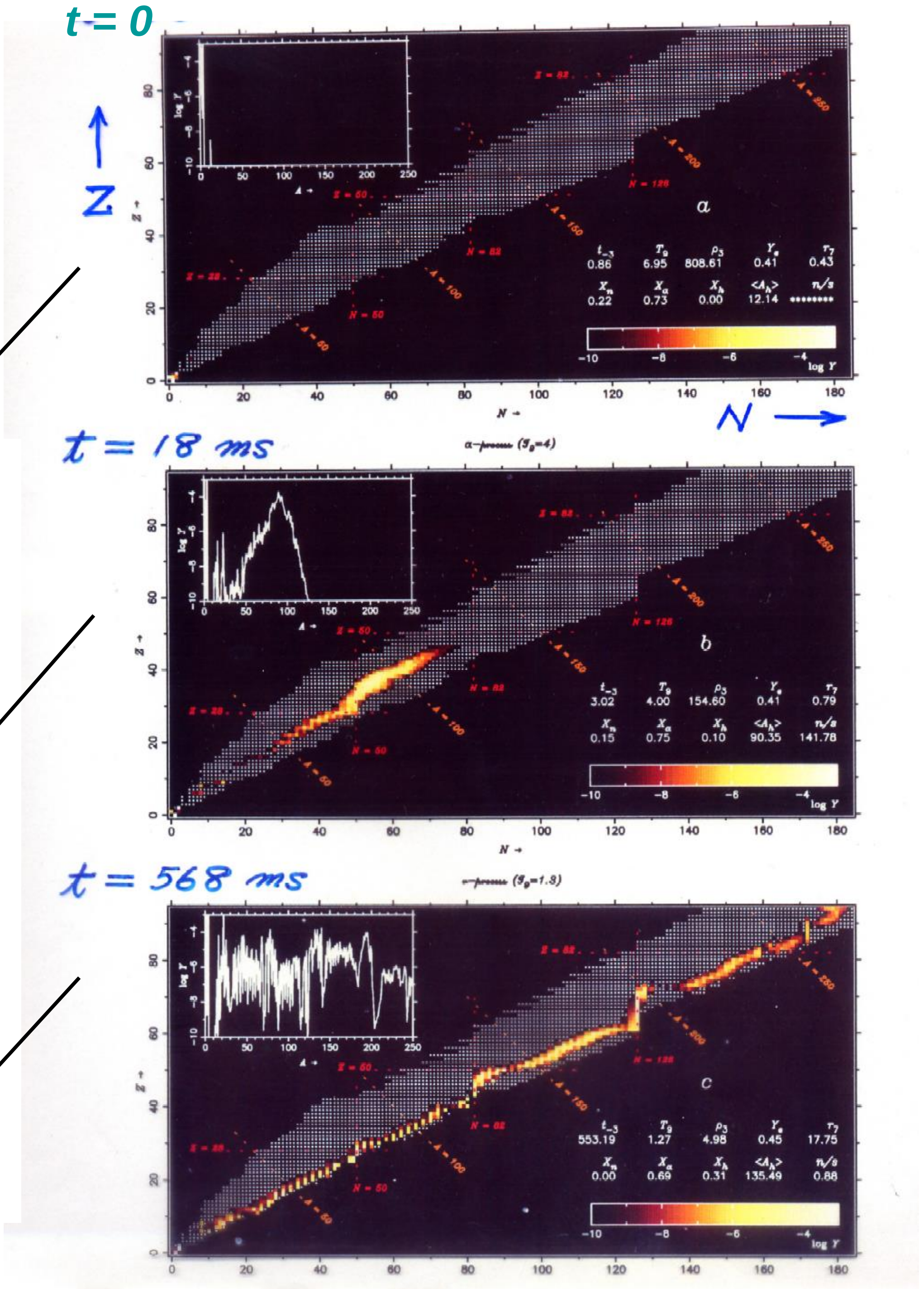
Mass Formula: FRDM (Moeller & Kratz)

Suzuki, Kajino, et al., ApJ 859 (2018), 133.



Supernova & Collapsar r-process Model

Otsuki, Tagoshi, Kajino & Wanajo 2000, ApJ 533, 424;
Wanajo, Kajino, Mathews & Otsuki 2001, ApJ 554, 578



t = 0

Neutrino-driven wind forms right after SN core collapse.

n + α + p

t = 18 ms

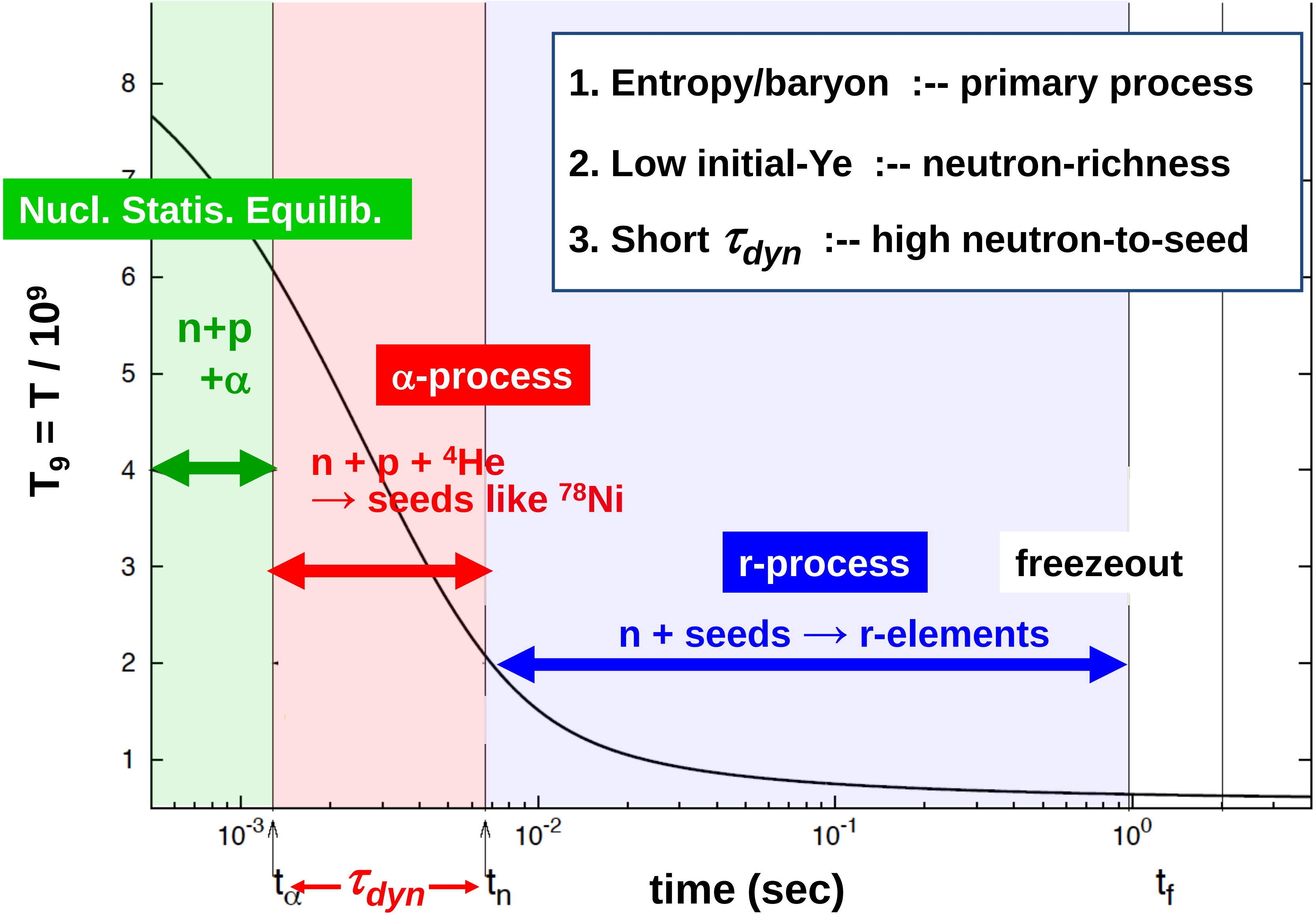
Seeds form.

Exotic neutron-rich; ^{78}Ni

t = 568 ms – 1 s

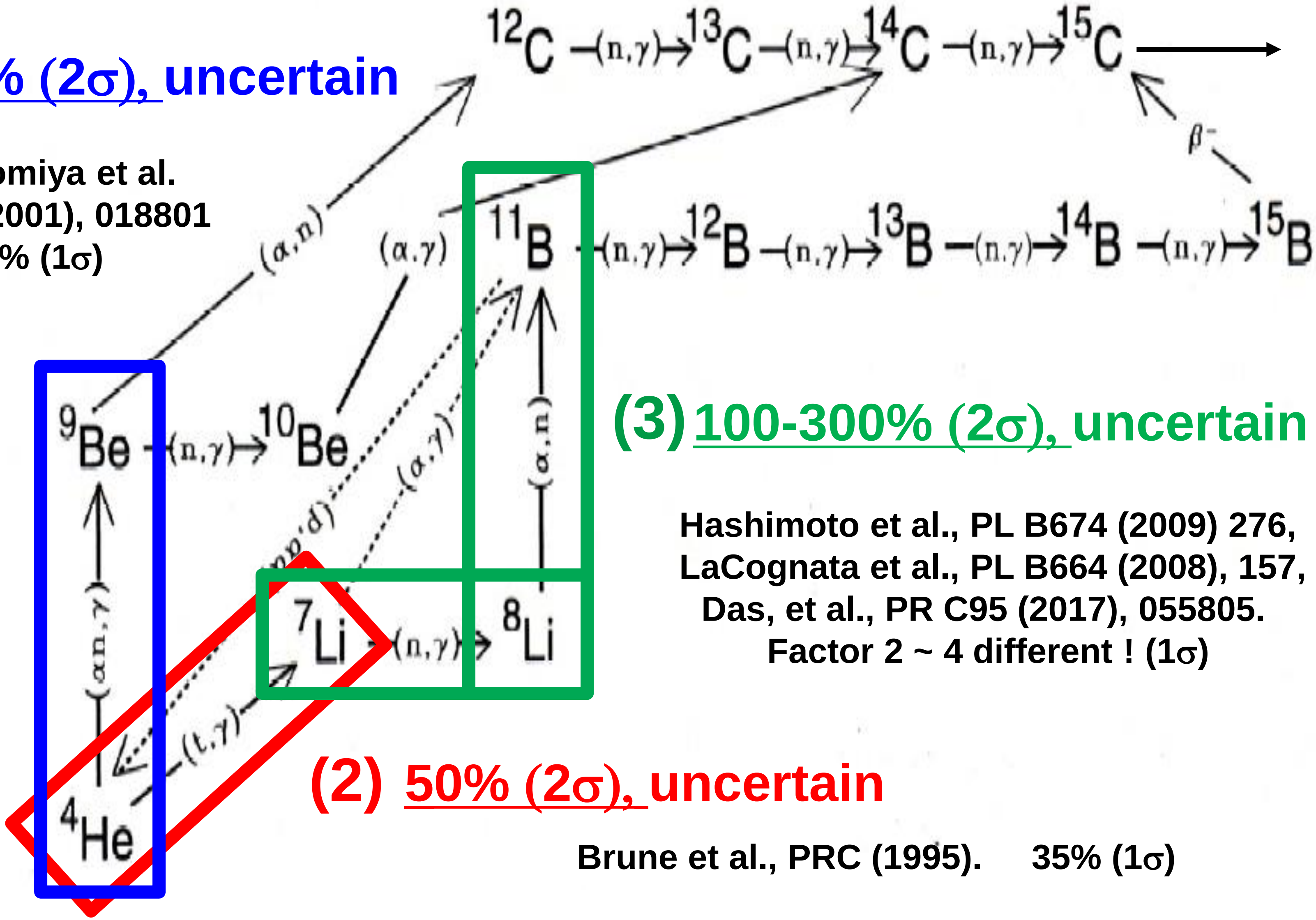
Heavy r-elements form.

Nucleosynthesis proceeds: NSE → α-process → r-process



1. **Entropy/baryon :-- primary process**
2. **Low initial-Ye :-- neutron-richness**
3. **Short τ_{dyn} :-- high neutron-to-seed**

Identified Important Reaction Flow Paths



30-100% (2σ), uncertain

Utsunomiya et al.
PRC63 (2001), 018801
35% (1σ)

(1)

(3) 100-300% (2σ), uncertain

Hashimoto et al., PL B674 (2009) 276,
LaCognata et al., PL B664 (2008), 157,
Das, et al., PR C95 (2017), 055805.
Factor 2 ~ 4 different ! (1σ)

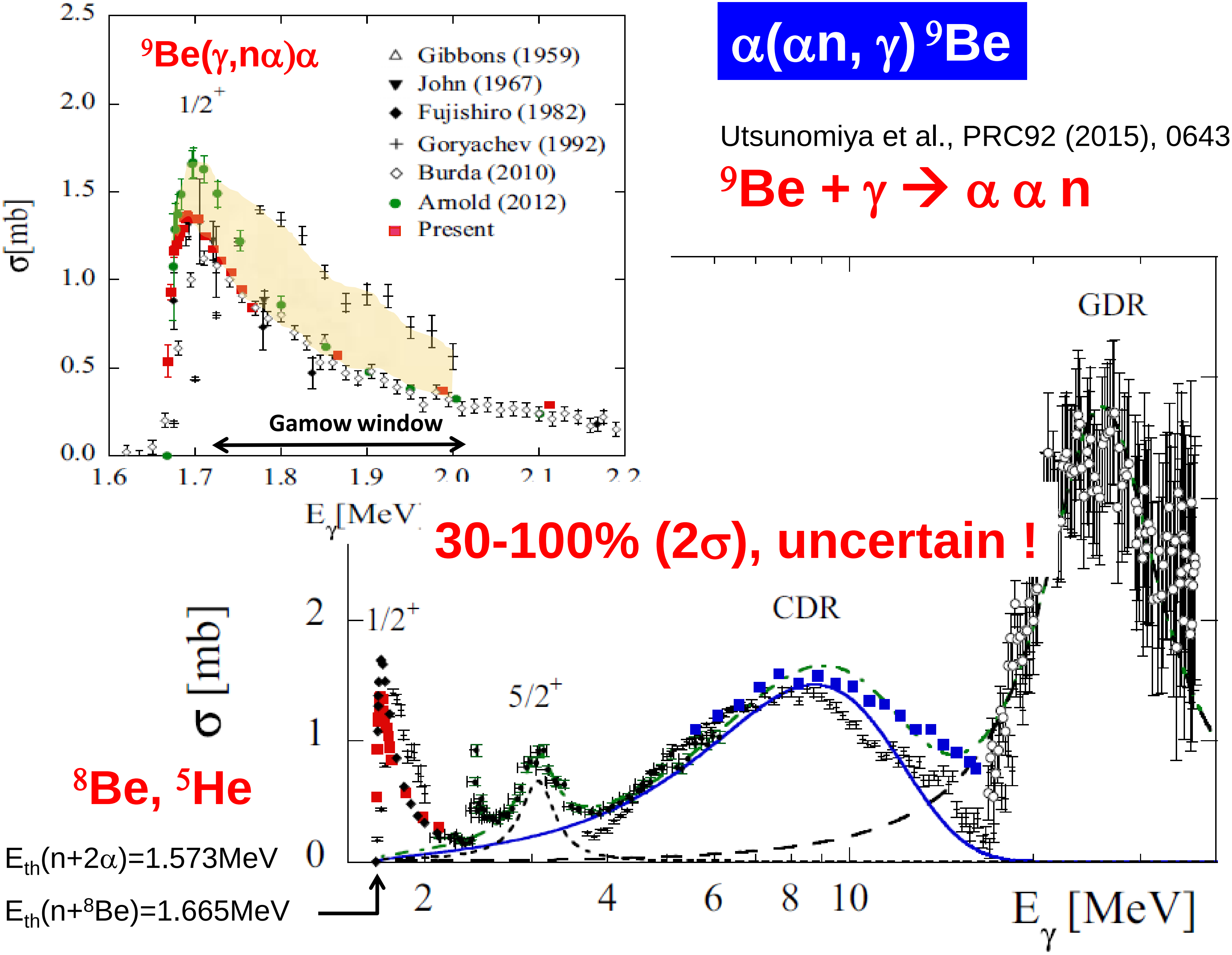
(2) 50% (2σ), uncertain

Brune et al., PRC (1995). 35% (1σ)

$\alpha(\alpha n, \gamma)\,^9Be$

Utsunomiya et al., PRC92 (2015), 064323.

$^9Be + \gamma \rightarrow \alpha\ \alpha\ n$



30-100% (2σ), uncertain !

^8Be, ^5He

$E_{th}(n+2\alpha)$=1.573MeV

$E_{th}(n+^8Be)$=1.665MeV

Principle of the Detailed Balance

CPT = 1, T: Time Reversality

P: Parity Conservation

$$\overset{1}{A} + \overset{2}{p} \longrightarrow \overset{\gamma}{\gamma} + \overset{c}{C^*}$$

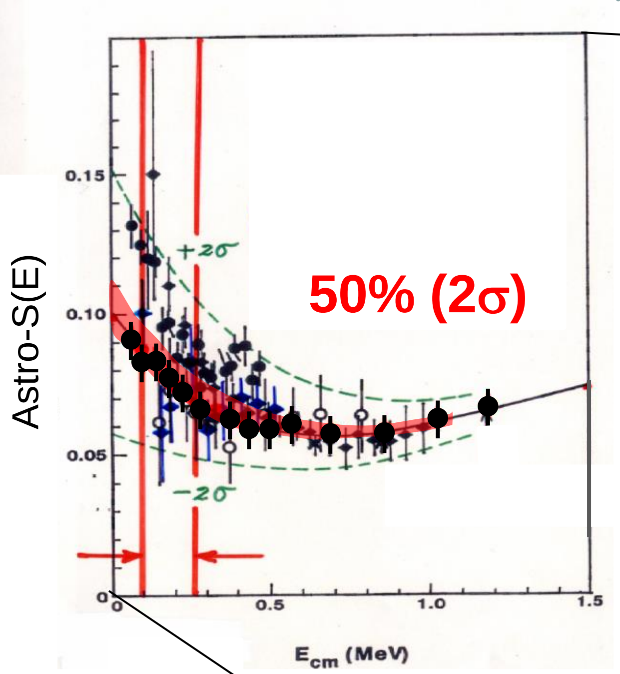
Radiative-Capture Reaction

Photo-Disintegration Reaction

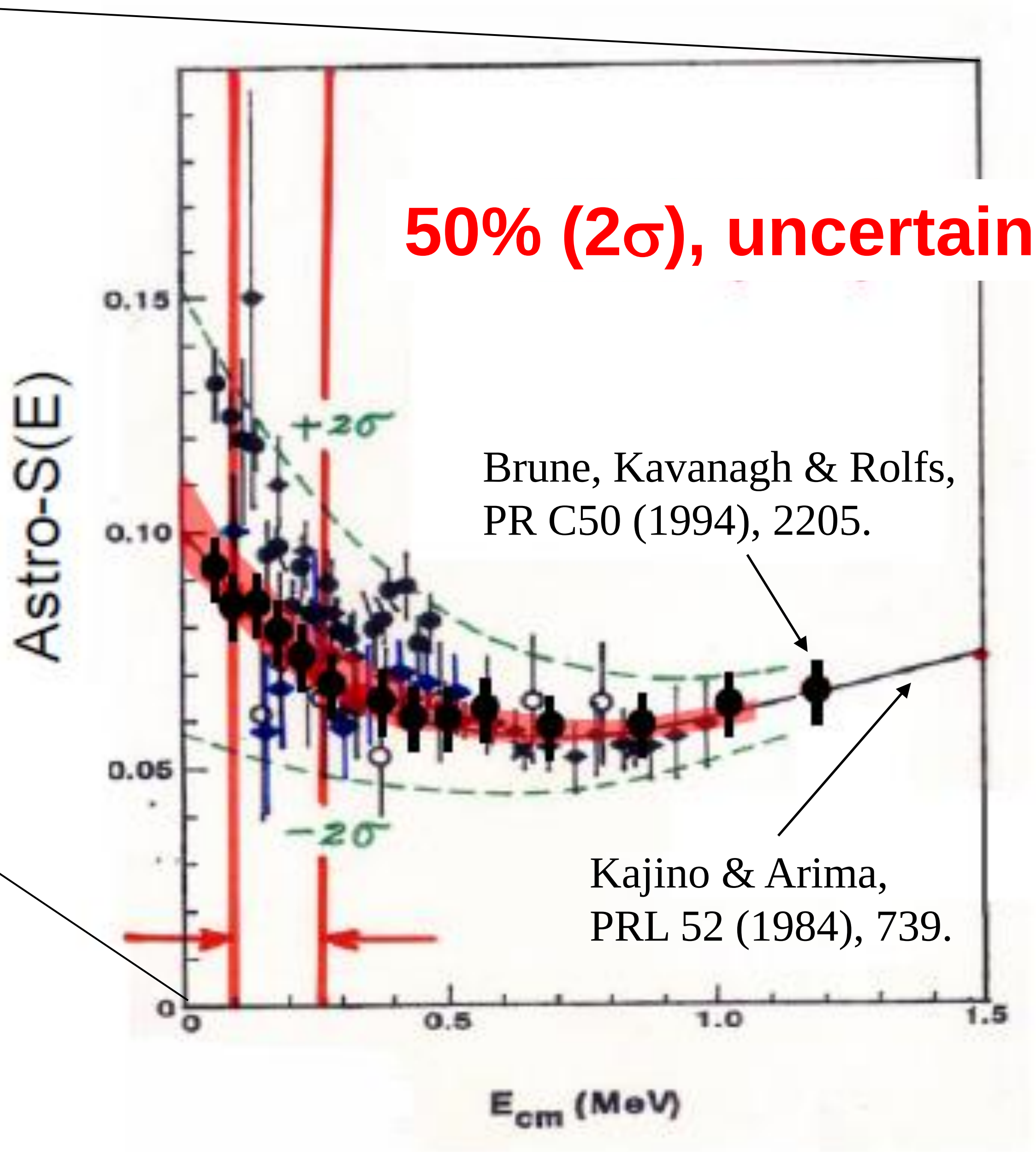
$$\boxed{\sigma^{DC}_{(p,\gamma)}(E)} = \frac{1}{E}\exp\left(\frac{-2\pi Z_1 Z_2 e^2}{\hbar v}\right) S^{DC}_{(p,\gamma)}$$

$$= \left[\frac{2(2J_c+1)}{(2J_1+1)(2J_2+1)}\right]\left(\frac{\kappa_\gamma}{k}\right)^2 \boxed{\sigma_{(\gamma,p)}(E_\gamma),}$$

$^4He(^3H,\gamma)^7Li$ ⟵ Mirror Conjugation ⟶ $^4He(^3He,\gamma)^7Be$



50% (2σ)



50% (2σ), uncertain

Brune, Kavanagh & Rolfs,
PR C50 (1994), 2205.

Kajino & Arima,
PRL 52 (1984), 739.

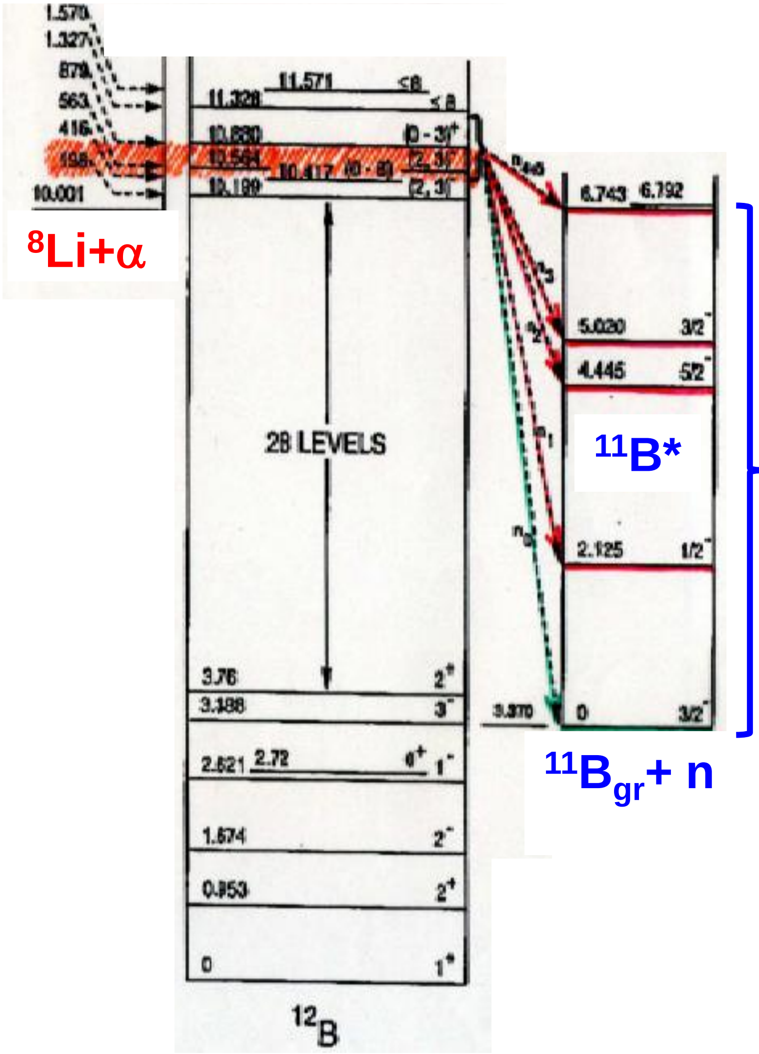
Kajino & Arima,
Phys. Rev. Lett. 52 (1984), 739;
Nncl. Phys. A413 (1084), 323;
Nncl. Phys. A460 (1986), 559;
Astrophys. J. 319 (1987), 531.

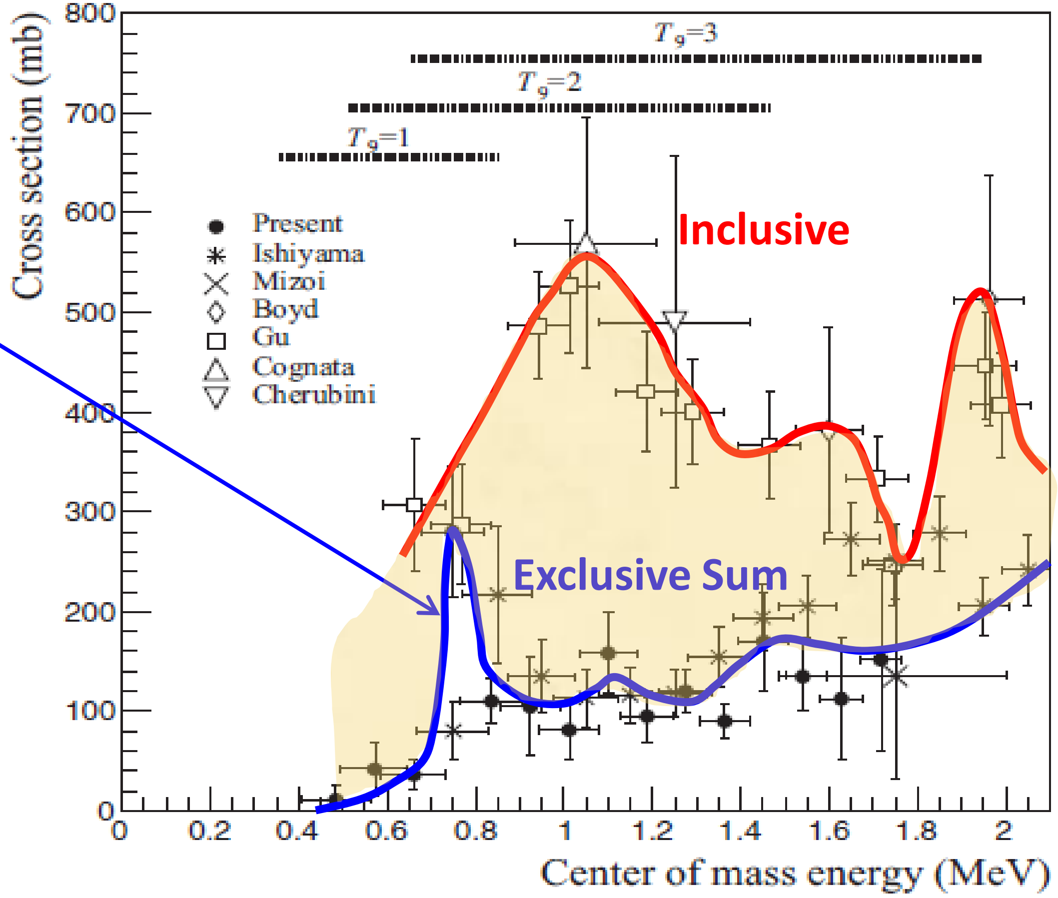
$^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

Discrepancy
Inclusive > Exclusive Sum ?

100-300% (2σ), uncertain !

- ◇ Boyd et al. Phys. Rev. Lett. 68 (1992), 1283.
- △ LaCognata et al., Phys. Lett. B664 (2008), 157.
- ☐ Gu et al., Phys. Lett. B343 (1995), 31.
- ✱ Ishiyama et al., Phys. Lett. B640 (2006), 82.
  Hashimoto et al., Phys. Lett. B674 (2009), 276.
- ● Das, et al., Phys. Rev. C95 (2017), 055805.



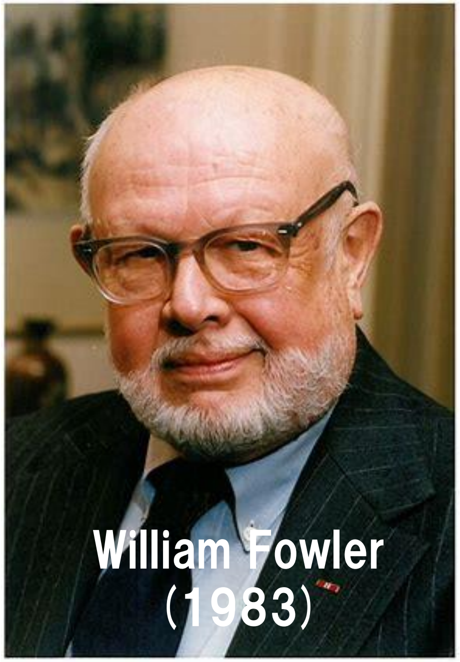


Content

1. Big-Bang Cosmology

2. Supernova and Merger

3. ν -Oscillation


William Fowler
(1983)


Masatoshi Koshiba
(2002)
Takaaki Kajita
(2015)

Why Neutrinos ? ⟺ Challenge of the Century

Universe is likely to be flat and acceleratingly expands:

$$\Omega_B + \Omega_{CDM} + \Omega_\Lambda = 1$$

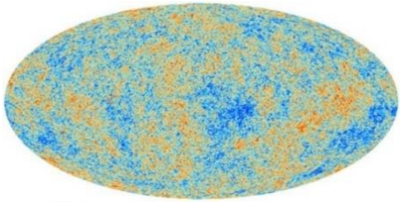
- ■ **What is CDM ($\Omega_{CDM} = 0.27$) and DE ($\Omega_\Lambda = 0.68$)?** ⇒ **CMB including $m_\nu \neq 0$**
- ■ **Is BARYON ($\Omega_B = 0.05$) sector well understood?**
  - **- BBN ^{7}Li-Problem** ⇒ **solved within "Standard Model" ?**
  - **- SUSY-DM** ⇒ **beyond "Standard Model"** ⇒ **$m_\nu \neq 0$ (beyond Higgs) Unique Signal !**

ν takes the key !

● **CMB Anisotropies + LSS**

$\sum m_\nu < 0.2$ eV (2σ, $B_\lambda < 2$nG): WMAP-7yr + HST + CMASS + Magnetic Field

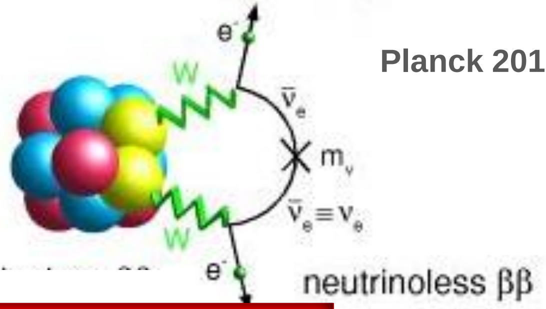
Ymazaki, Kajino, Mathews & Ichiki, Phys. Rep. 517 (2012), 141; PR D81 (2010), 103519.



Planck 2013

● **0νββ in COUORE, NEMO3, EXO, KamLAND Zen**

$|\sum U^2_{e\beta} m_\beta| < 0.3$ eV: COUORE, NEMO3, EXO, KamLAND Zen

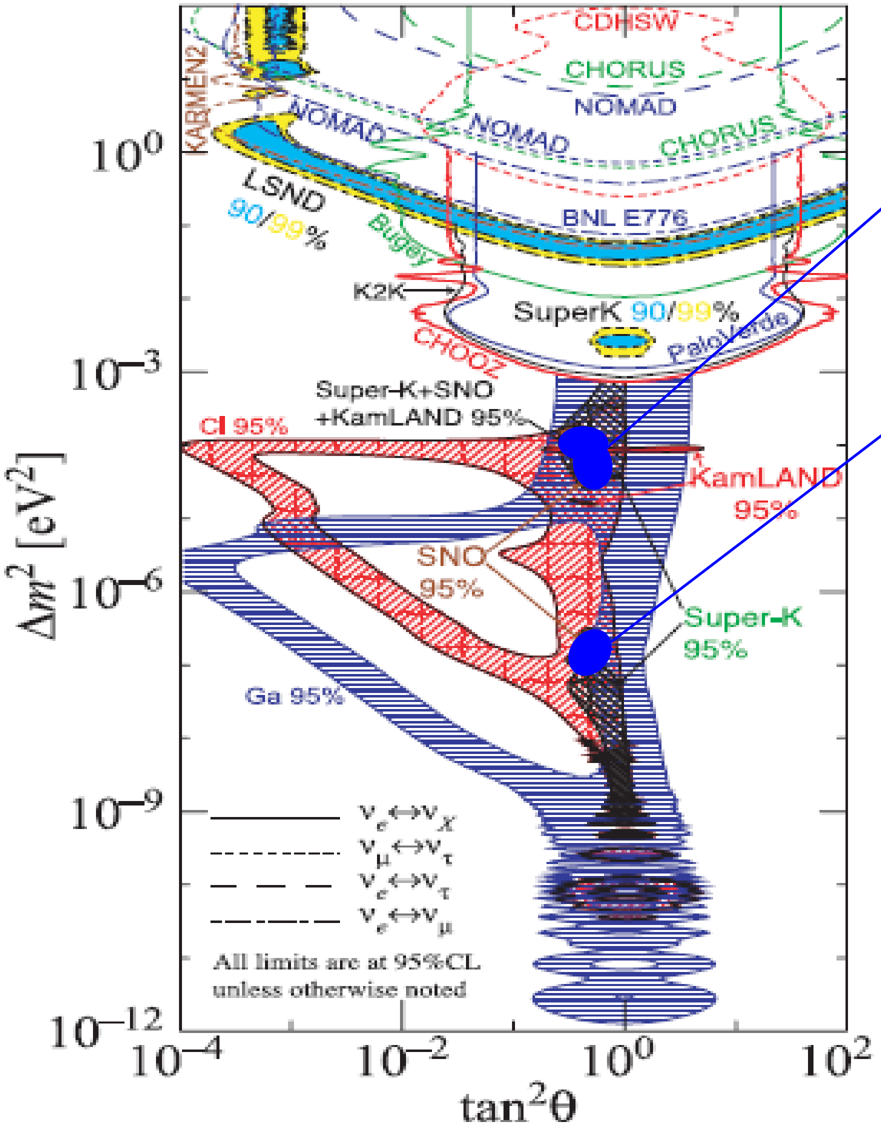


● **ν-OSCILLATION** ⟹ **0.05 (Normal) ∼ 0.1 (Inverted)**

Mass Hierarchy takes the key ! Go to Supernova!

"KNOWN" of Neutrino Oscillations

KAMIOKANDE, SK, KamLand (reactor ν), SNO determined ⊿m_{12}^2 and θ_{12} uniquely, and also SK (atmospheric ν) determined ⊿m_{23}^2 and θ_{23} uniquely.



23－mixing

$\sin^2 2\theta_{23} = 1.0$

$|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2

12－mixing Cabibbo angle

$\sin^2 2\theta_{12} = 0.816$ $(\theta_{12}+\theta_C=\pi/2)$

$\Delta m^2_{12} = 7.9 \times 10^{-5}$ eV^2

"UNKNOWN"

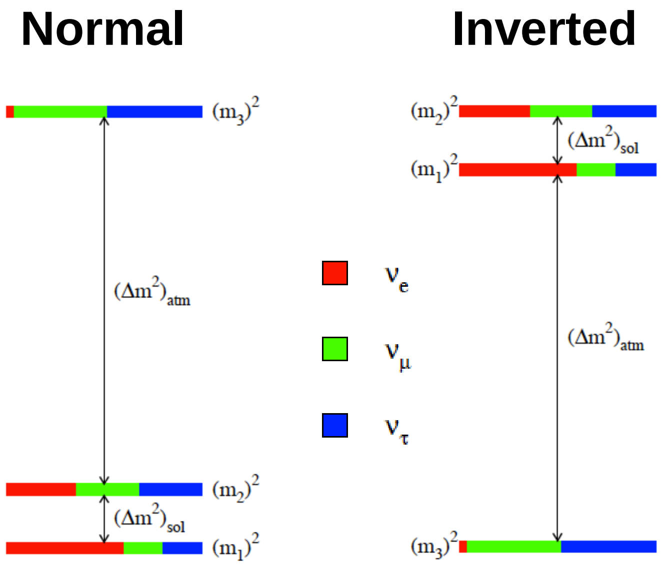
13－mixing

- $\sin^2 2\theta_{13}$ (< 0.1)
- ⊿$m_{13}^2 = \pm 2.4\text{x}10^{-3}$ eV^2
- ~~Absolute Mass~~
- ~~δ=CP-phase~~

E(νμ)=E(ντ): Yokomakura et al., PL B544, 286.

Significance of ν-Oscillation

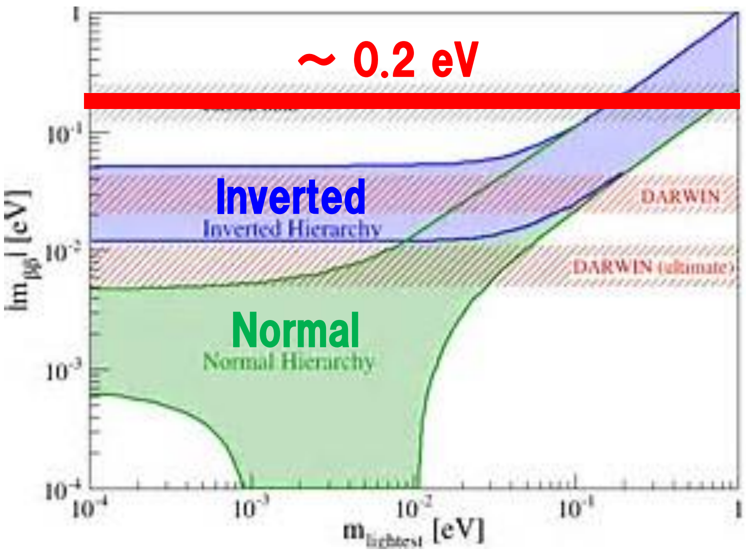
ν−Mass Hierarchy, UNKNOWN !



$\Delta m^2_{12} = 7.9\times10^{-5}\text{eV}^2$ $|\Delta m^2_{23}| = 2.4\times10^{-3} = (0.05\text{ eV})^2$

Normal: $\Sigma\, m_\nu \sim 0.05$ eV !

Inverted: $\Sigma\, m_\nu \sim 0.1$ eV !



Purpose

:- to constrain MSW and Collective ν-Oscillation and Mass Hiararchy from Supernova Nucleosynthesis

Physics of Neutrino Oscillation

Dirac Equation（Dirac-Pauli）

$$(i\gamma^\mu \partial_\mu - m)\psi(x) = 0$$

$$\alpha = \begin{pmatrix} 0 & \sigma \\ \sigma & 0 \end{pmatrix}, \quad \gamma_0 = \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$$\gamma = \beta\alpha = \begin{pmatrix} 0 & \sigma \\ -\sigma & 0 \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Eigen-State of Free Neutrinos with (E, p)（for m = 0）

$$\psi = u \, \boxed{\exp\frac{i}{\hbar}(pr - Et).}$$

Dirac spinor

L-neutrino (h=-1)

$$u(p, 1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \quad \boxed{u(p, -1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix},} \quad E > 0$$

R-neutrino (h=+1)

$$\boxed{v(p, 1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix},} \quad v(p, -1) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \\ 0 \\ 1 \end{pmatrix}, \quad E < 0$$

Neutrino flavor oscillation (of vacuum, MSW, or self-interaction effects) does not change the spinor structure due to weak interactions

➡ Therefore, only the propagation of energy eigen-state is important !

Neutrino Flavor Oscillation for Matter（MSW） Effect

$$i\hbar\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\left\{U\begin{pmatrix}0 & & \\ & \Delta m^2_{21}c^4/2\varepsilon_\nu & \\ & & \Delta m^2_{31}c^4/2\varepsilon_\nu\end{pmatrix}U^+ + \boxed{A(n_e)}\right\}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavor eigenstate *MNS matrix* *mass eigenstate*

(Maki, Nakagawa, Sakata , *1962)*

$$\boxed{A(n_e)=\begin{pmatrix}\pm\sqrt{2}G_F(\hbar c)^3 n_e & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}}$$

n_e = Electron Number Density

○ m²–difference $\Delta m^2_{ji}\equiv m_j^2-m_i^2$ ⟶ Mass hierarchy, unknown !

○ Mixing angle $s_{ij}\equiv\sin\theta_{ij}$, $c_{ij}\equiv\cos\theta_{ij}$ ⟶ θ_{13}, unknown !

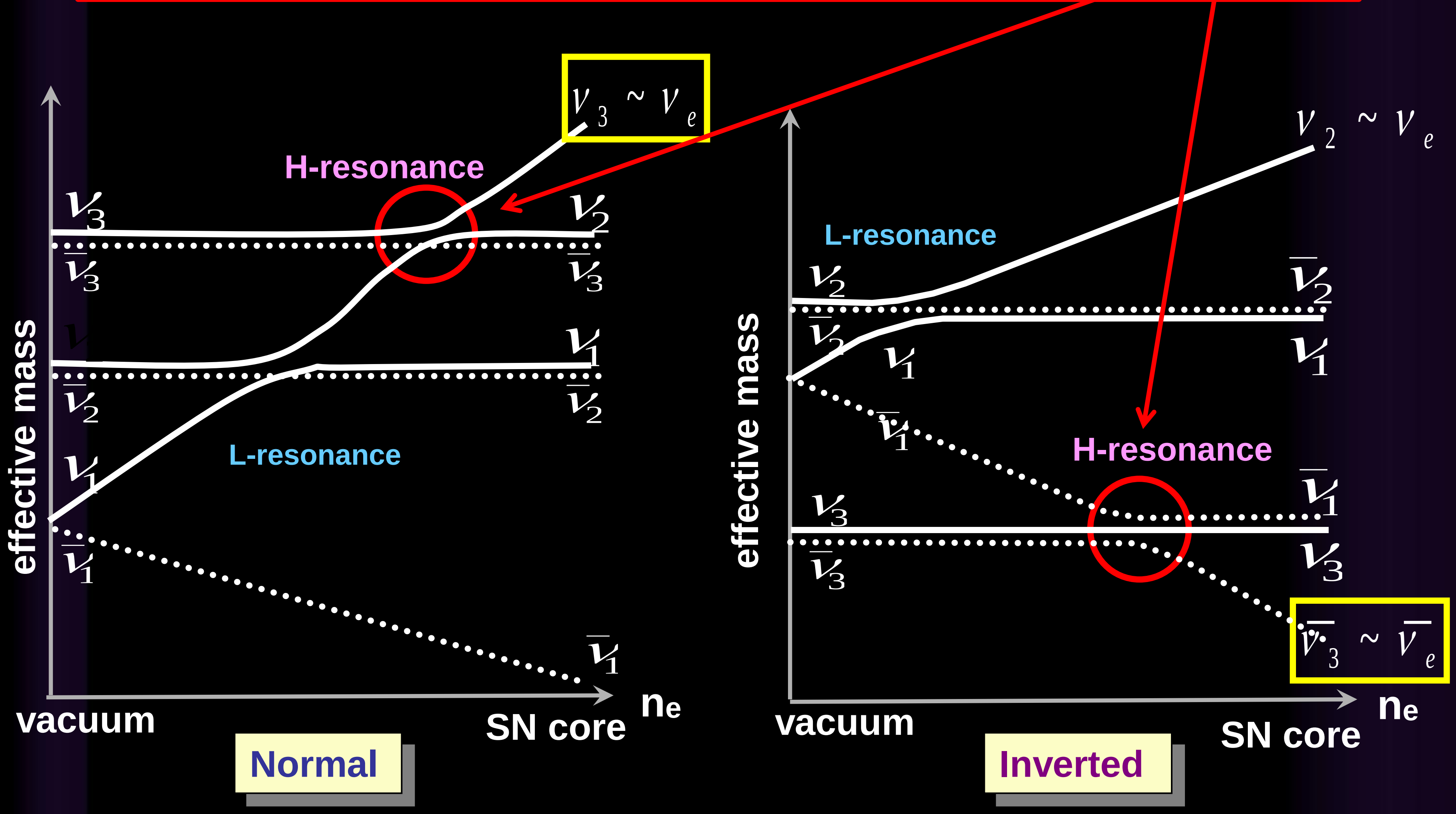
○ CP Phase, independent on δ

Kobayashji & Masukawa 1973

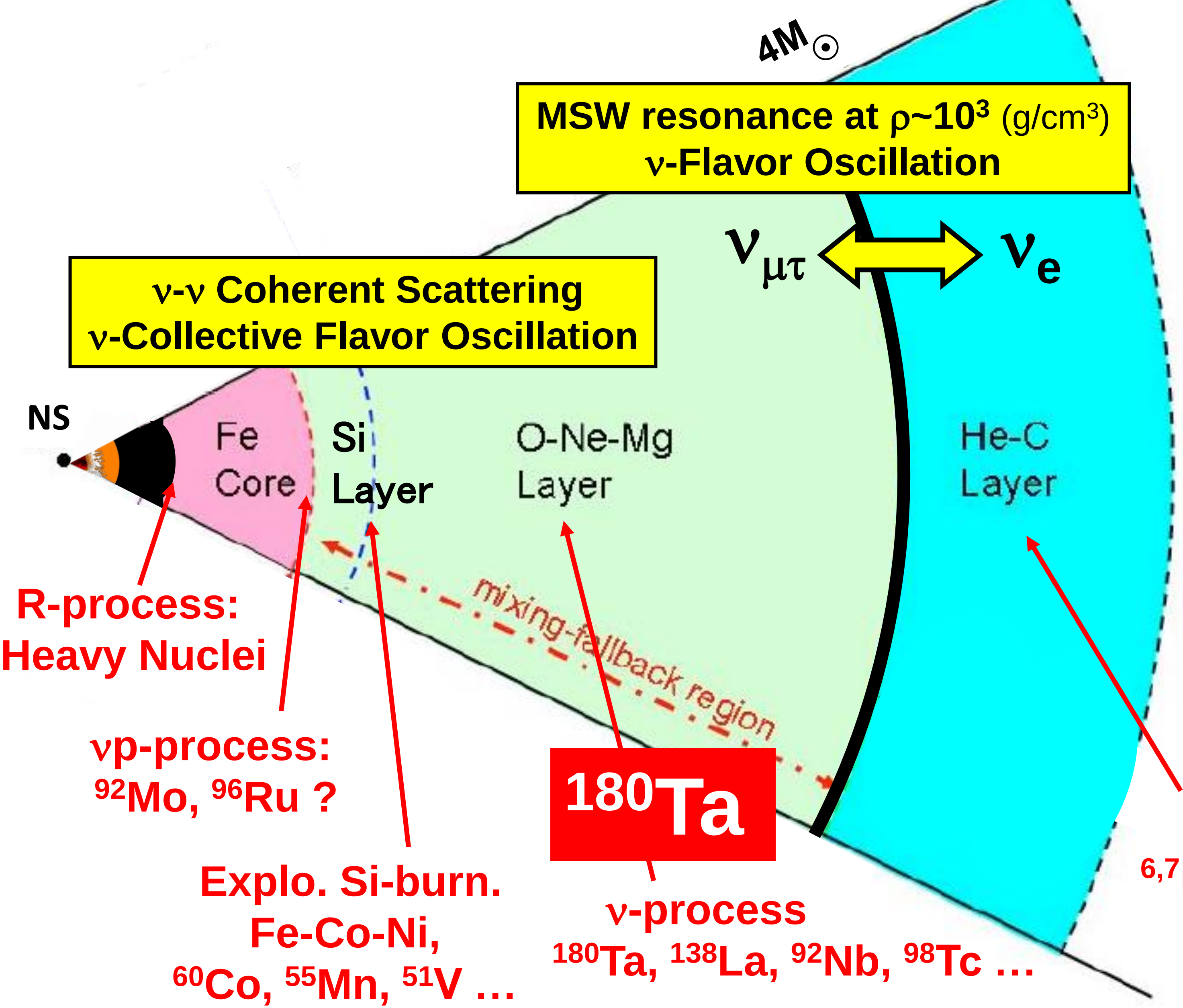
Yokoyama, et al. PL B544, 286.

MSW Matter Effect & Mass Hierarchy

$$\rho_{\text{res}} Y_e = \frac{m_u \Delta m_{ji}^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_F (\hbar c)^3 \varepsilon_\nu} = 6.55 \times 10^6 \left(\frac{\Delta m_{ji}^2}{1 \text{ eV}^2}\right)\left(\frac{1 \text{ MeV}}{\varepsilon_\nu}\right) \cos 2\theta_{ij} \sim 10^3 \text{ g/cm}^3$$



Various roles of ν's in SN-nucleosynthesis



MSW resonance at ρ~10^3 (g/cm^3)
ν-Flavor Oscillation

ν-ν Coherent Scattering
ν-Collective Flavor Oscillation

R-process:
Heavy Nuclei

νp-process:
^{92}Mo, ^{96}Ru ?

Explo. Si-burn.
Fe-Co-Ni,
^{60}Co, ^{55}Mn, ^{51}V …

^{180}Ta

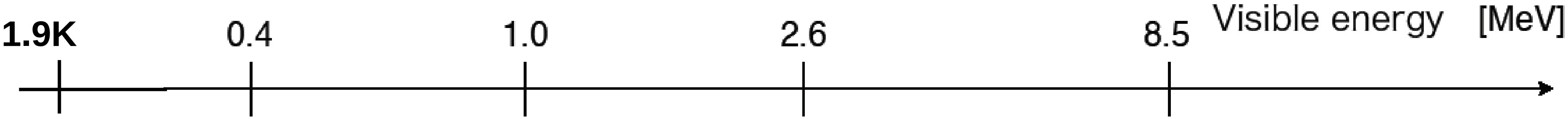
ν-process
^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

ν-process:
^{6,7}Li, ^{9}Be, ^{10,11}B …


Hirokazu Sasaki


Xingqun Yao

Various Neutrino-Sources in Nature/Culture



neutrino electron elastic scattering

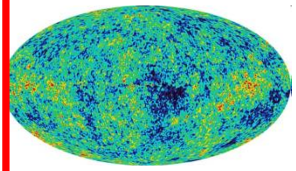
$\nu + e^- \rightarrow \nu + e^-$

inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$

CMB

Cosmic Background



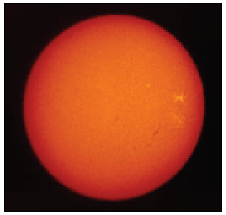
Neutrino Cosmology

verification of particle model

ν_e, ν_μ, ν_τ

$\overline{\nu_e}, \overline{\nu_\mu}, \overline{\nu_\tau}$

^{7}Be solar neutrino



Neutrino Astrophysics

verification of SSM

ν_e

atmospheric neutrino
geo-neutrino

Neutrino Geophysics

verification of earth evolution model

$\overline{\nu_e}$ or ν_e ν_μ $\overline{\nu_e}$ $\overline{\nu_\mu}$

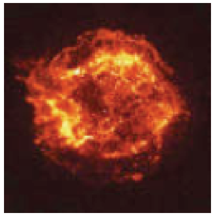
reactor neutrino

Neutrino Physics

Precision measurement of oscillation parameters

$\overline{\nu_e}$

supernova relic neutrino etc.



Neutrino Cosmology

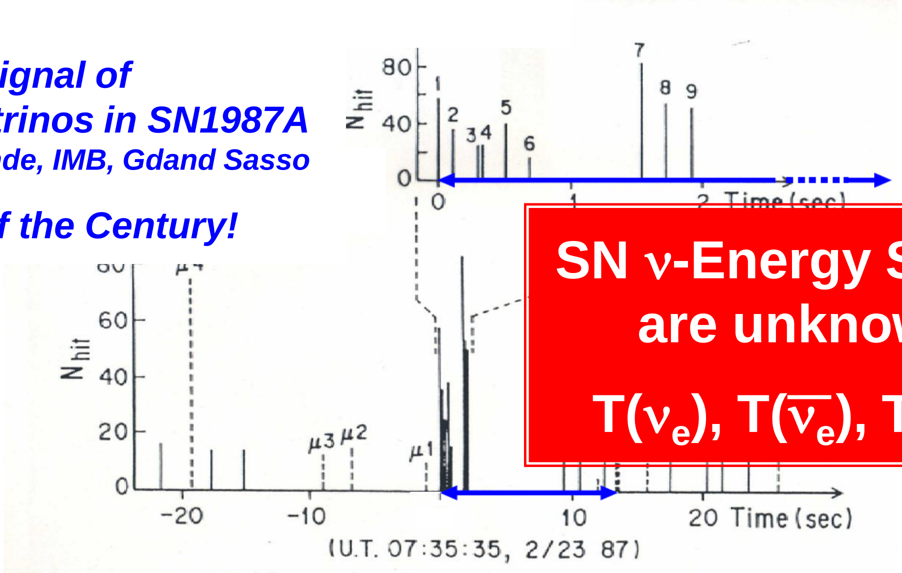
verification of universe evolution

ν_e, ν_μ, ν_τ

$\overline{\nu_e}, \overline{\nu_\mu}, \overline{\nu_\tau}$

Direct signal of
SN neutrinos in SN1987A
Kamiokande, IMB, Gdand Sasso

Event of the Century!



SN ν-Energy Spectra are unknown !

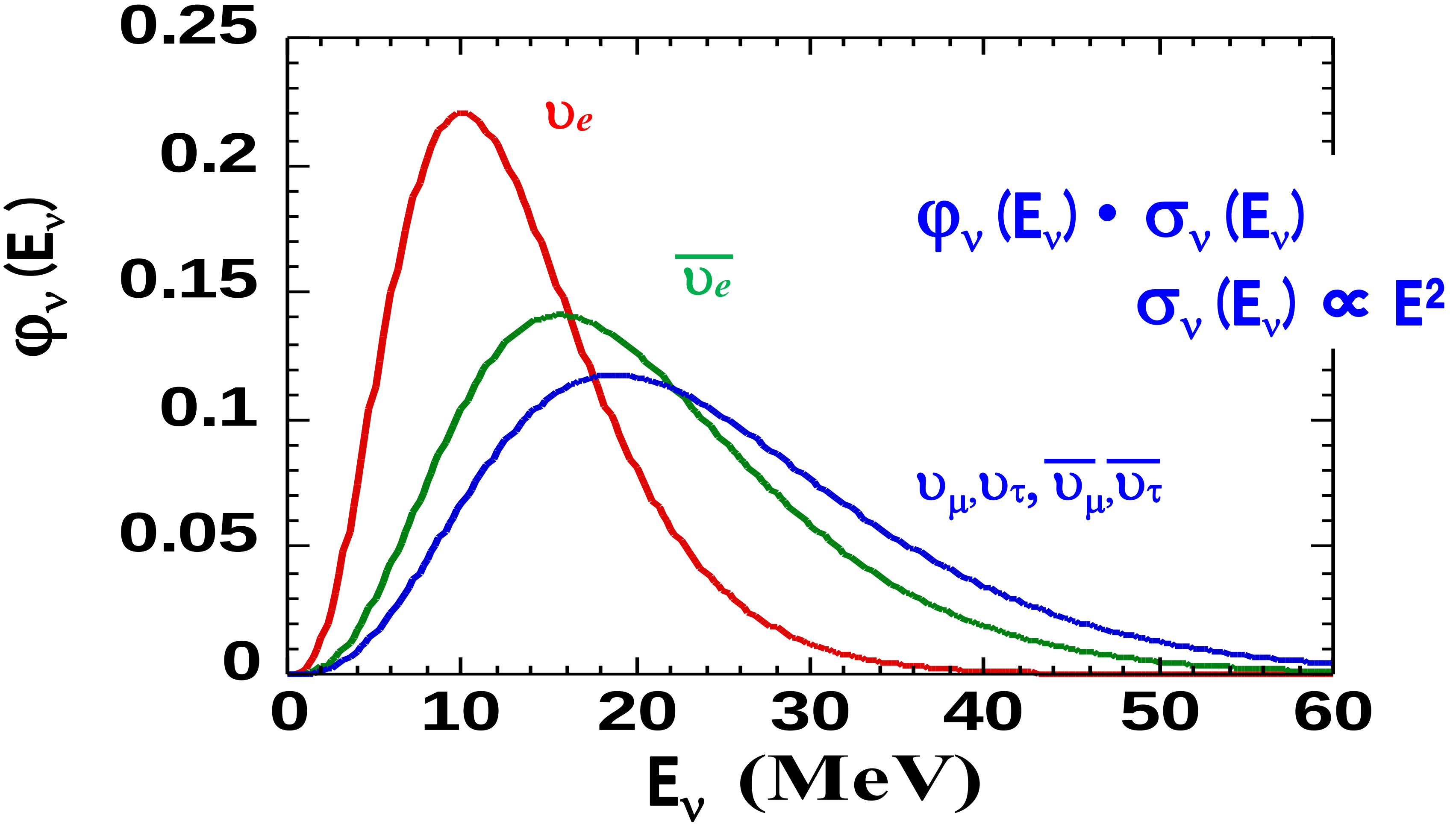
$T(\nu_e)$, $T(\overline{\nu_e})$, $T(\nu_x)$?

Original by courtesy of K. Inoue

EXPECTED Neutrino Energy Spectra

Kajino, Mathews & Hayakawa, J. Phys. G41 (2014), 044007;
Hayakawa, Kajino et al., Phys. Rev. Lett. 121 (2018), 102701.

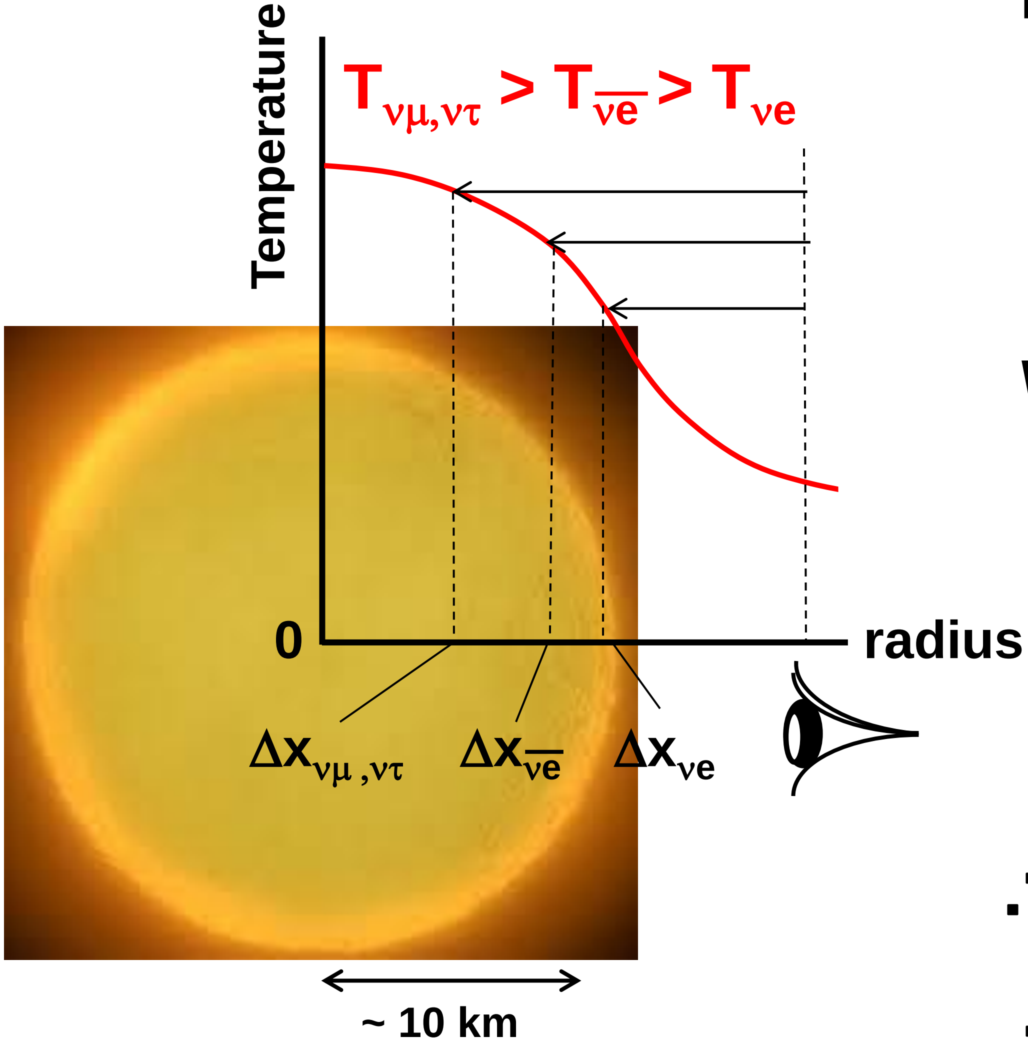
$T(\nu_e) < T(\overline{\nu_e}) < T(\nu_x)$ $x = \nu_\mu, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$



$\varphi_\nu(E_\nu) \cdot \sigma_\nu(E_\nu)$

$\sigma_\nu(E_\nu) \propto E^2$

Temperature Hierarchy of Supernova－ν



Proto-Neutron Star

Neutrino diffusion process

$$\Delta x_\nu^2 = 2D_\nu \tau_\nu$$

$$D_\nu = \lambda_\nu c/3$$

$$\lambda_\nu = (n_T\, \sigma_\nu)^{-1}$$

Weak interactions

$$\nu_e + n \rightarrow p + e^- \text{ (CC)}$$

$$\overline{\nu_e} + p \rightarrow n + e^+ \text{ (CC)}$$

$$\nu_i + p,n \rightarrow p,n + \nu_i \text{ (NC)}$$

$(i = e, \mu, \tau)$

$$\therefore\ \lambda_{\nu e} < \lambda_{\overline{\nu e}} < \lambda_{\nu\mu,\nu\tau}$$

$$\therefore\ \Delta x_{\nu e}^2 < \Delta x_{\overline{\nu e}}^2 < \Delta x_{\nu\mu,\nu\tau}^{\ 2}$$

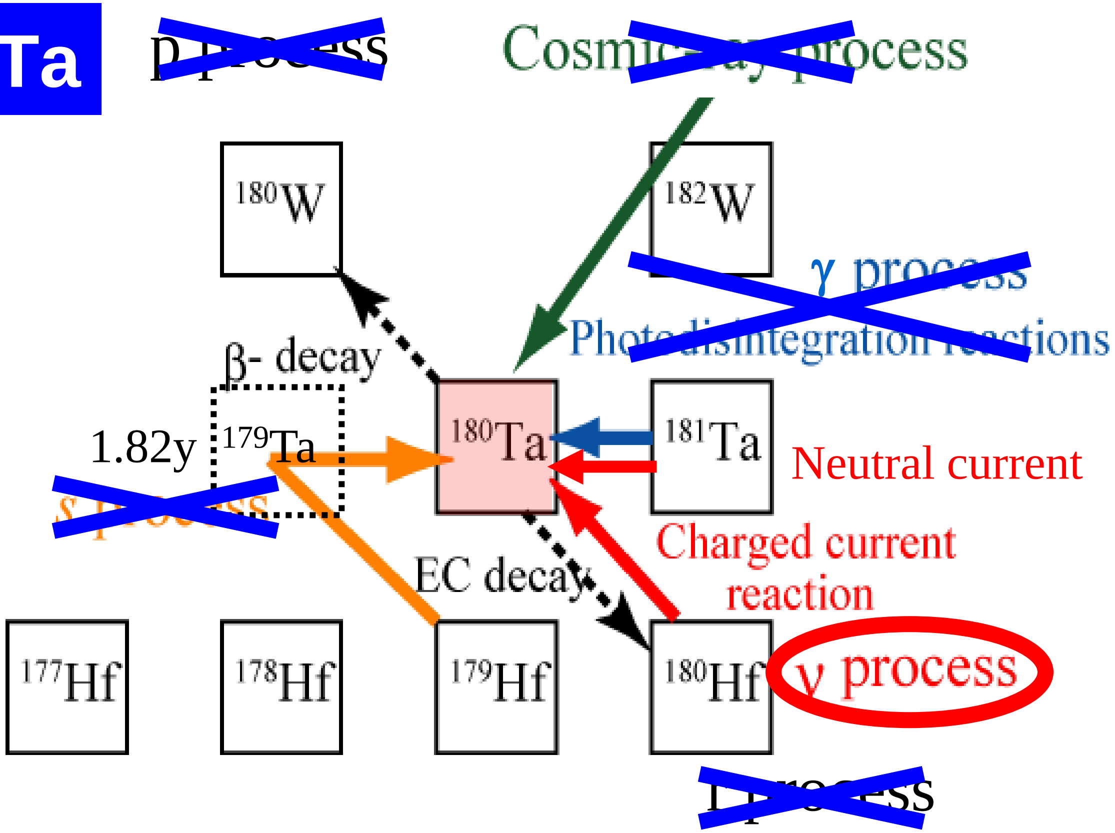
Missing Origin of ^{180}Ta

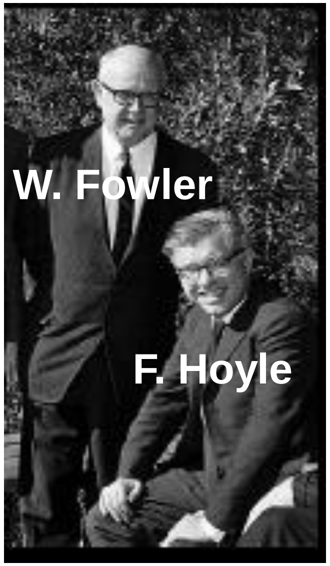
^{138}La = spherical
^{180}Ta = deformed

K.Yokoi, Nature (1983)
proposal of s-process origin.

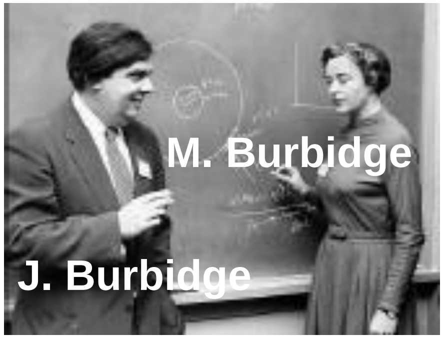
Belic et al., Phys. Rev. Lett. (1999)
Wisshak, Phys. Rev. Lett. (2001)

S-process cannot produce both ^{138}La & ^{180}Ta.





B^{2}FH,
RMP. 29 (1957), 547-650.
"Element Genesis in Stars"



Supernova neutrino-process:

Nucleosynthesis Theory

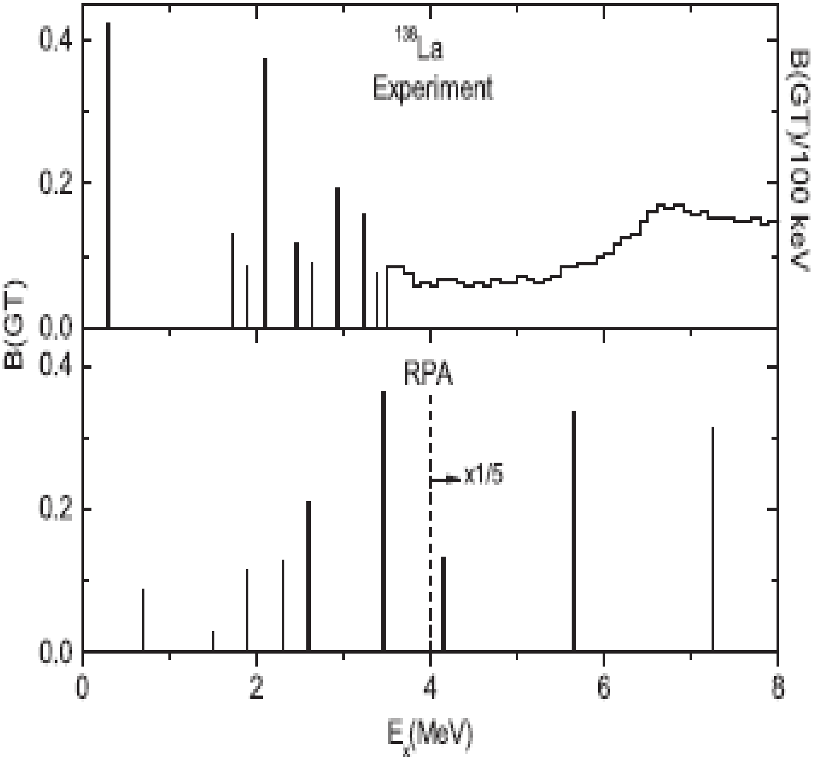
Woosley, Hartmann, Hoffman, & Haxton,
ApJ 356 (1990), 272.
Heger et al., Phys. Lett. B 606, 258 (2005)

Nucleo-Cosmochronology:

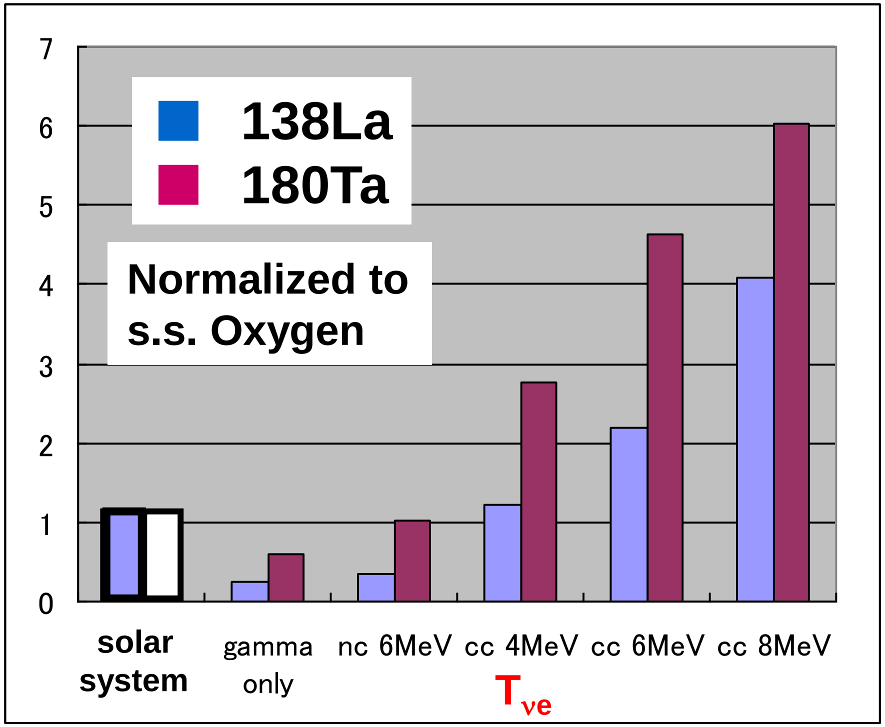
Hayakawa, Shimizu, Kajino, Ogawa, & Nakada,
PRC 77 (2008), 065802; 79 (2009) 059802.

Impact of CEX Reaction on ν-Process

Byelikov + Fujita et al., PRL (2007), RCNP measurement of GT strength.



A. Heger, Phys. Lett. B 606, 258 (2005)



- ★ OVERPRODUCTION of ^{180}Ta relative to ^{138}La!
- ★ Forbidden transitions + as well as GT contribute because neutrino energy spans E_ν = 0 ~ 80 MeV !

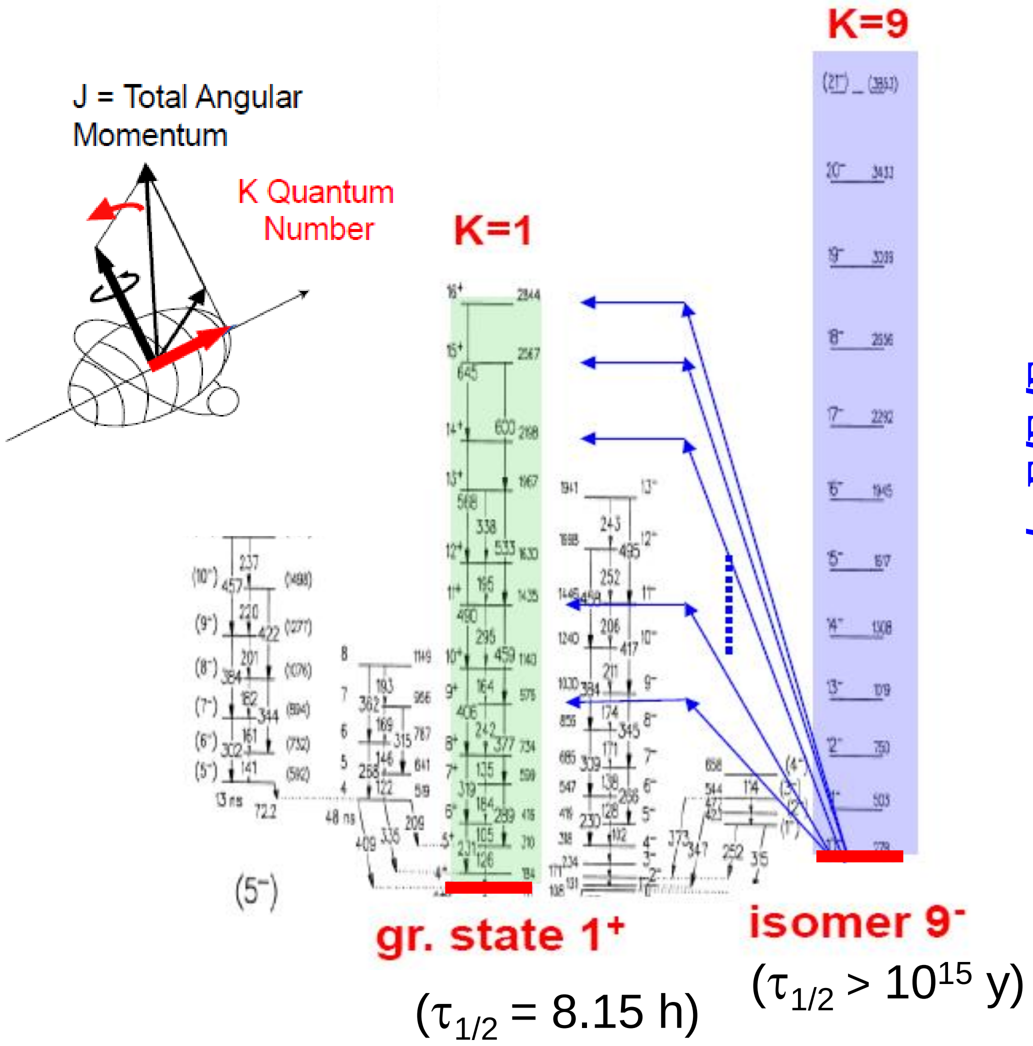
Gamma-Decay Widths of Excited States

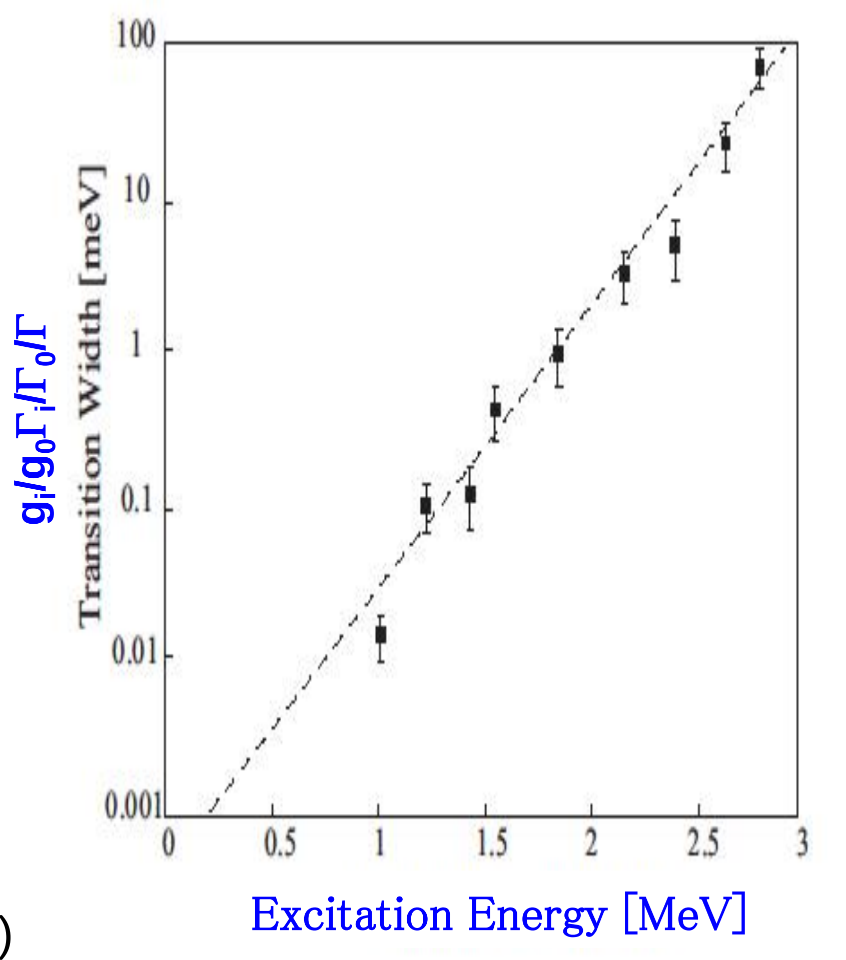
Saitoh et al. (NBI group), NPA 1999, ++
Dracoulis et al. (ANU group), PRC 1998, ++

Very small total decay width of $^{180}Ta_m$ was measured.

Linking transitions between K = 1 and 9 bands are extremely weak.

D. Belic et al., PR C65 (2002), 035801.





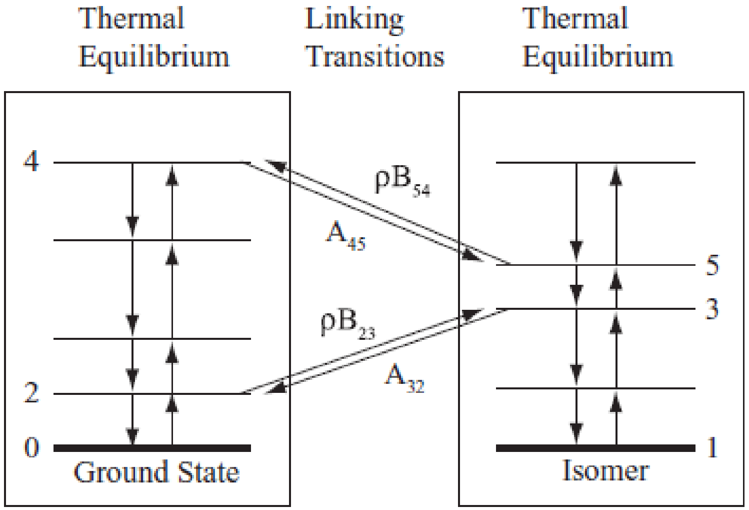
Formula to calculate time-dept linking transitions

Hayakawa, Kajino, Mohr, Chiba & Mathews, PR C81 (2010), 052801®; PR C82 (2010), 058801

★ General formula (Einstein AB theory) for $kT << \Delta E_{ij}$:

$$\frac{dN_0}{dt} = -\sum_{iP} P_i^g A_{ip} N_0 + \sum_{ip} P_i^m \rho B_{pi}(1-N_0), -\sum_{jq} P_j^g \rho B_{qj} N_0 + \sum_{jq} P_j^m A_{jq}(1-N_0)$$

$$= -\sum_{i\,p} P_0^g \frac{g_i}{g_0} exp(-(E_i-E_0)/kT) A_{ip} N_0 + \sum_{ip} P_1^m \frac{g_i}{g_1} exp(-(E_i-E_1)/kT) A_{ip}(1-N_0),$$



1+ 9-

$$m_i/m_j = (2J_i+1)/(2J_j+1)exp(-(E_i-E_j)/kT),$$

$$P_i \equiv m_i/m_{total} = \frac{m_i/m_0}{\sum(m_i/m_0)}.$$

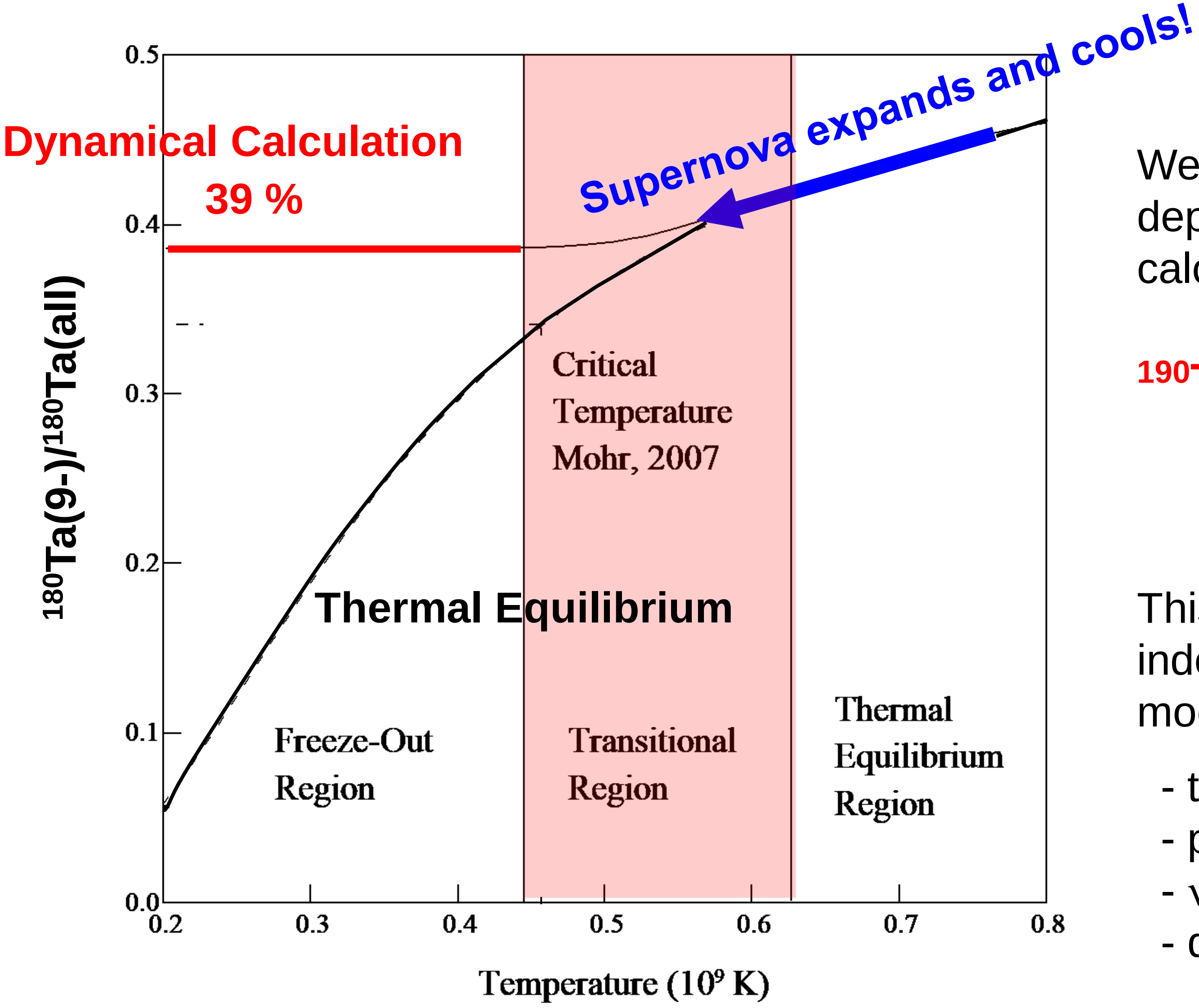
★ In the SPECIFIC case of ^{180}Ta:

Transition prob. $\Sigma_p A_{ip} = \Gamma_i / \hbar$ ← Exp.

$$\frac{dN_0}{dt} = -\sum_i P_0^g \frac{g_1}{g_0} exp(-(E_i-E_0)/kT) \boxed{\frac{g_i}{g_1}\frac{\Gamma_i}{\hbar}} N_0 + \sum_i P_1^m exp(-(E_i-E_1)/kT) \boxed{\frac{g_i}{g_1}\frac{\Gamma_i}{\hbar}} (1-N_0).$$

Calculated Result

Hayakawa, Mohr, Kajino, Chiba & Mathews, PR **C81** (2010), 052801®; **C82** (2010), 058801.



We carried out time-dependent dynamical calculations:

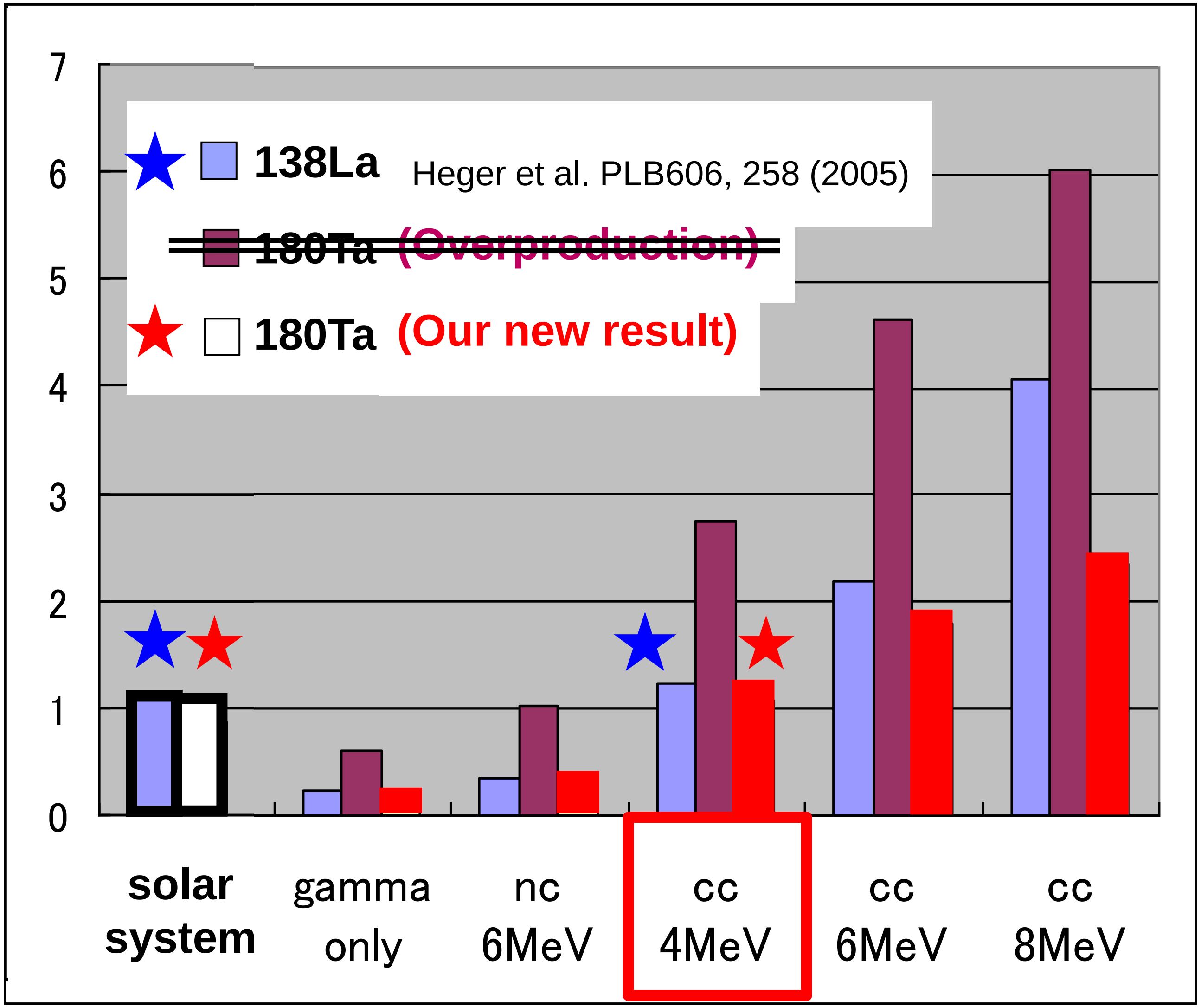
^{190}Ta(9$^-$)/^{190}Ta(all)
~ 0.39
survives!

This result is almost independent of SN model parameters, i.e.

- total explosion E,
- progenitor mass,
- ν-luminosity, and
- decay time scale.

Result from our ν-Nucleosynthesis

T. Hayakawa, P. Mohr, T. Kajino, S. Chiba, and G.J. Mathews, Phys. Rev. C81 (2010), 052801®; Phys. Rev. C82 (2010), 058801.



39% of $^{180}Ta^m$ survives in the dynamics of c.c. supernova explosion.

$$T_{\nu e} = T_{\overline{\nu e}}$$

= 4 MeV.

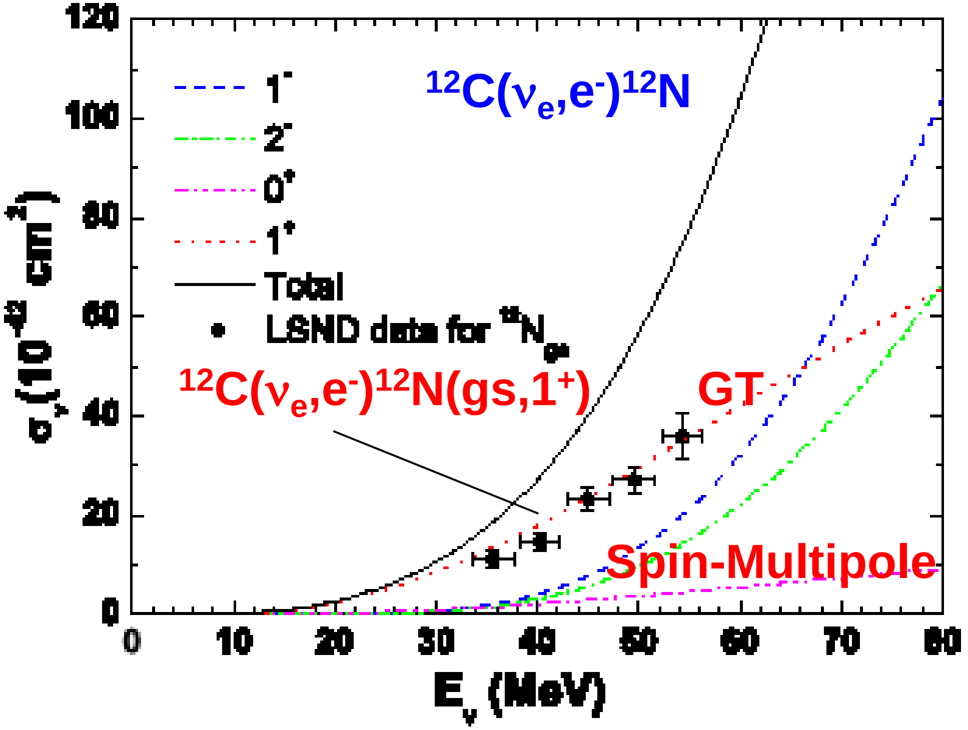
Consistent with r-process in ν-DW SN !

Neutrino-^{138}La, ^{180}Ta cross section calculations in Quasi-particle Random Phase Approx. & Shell Model

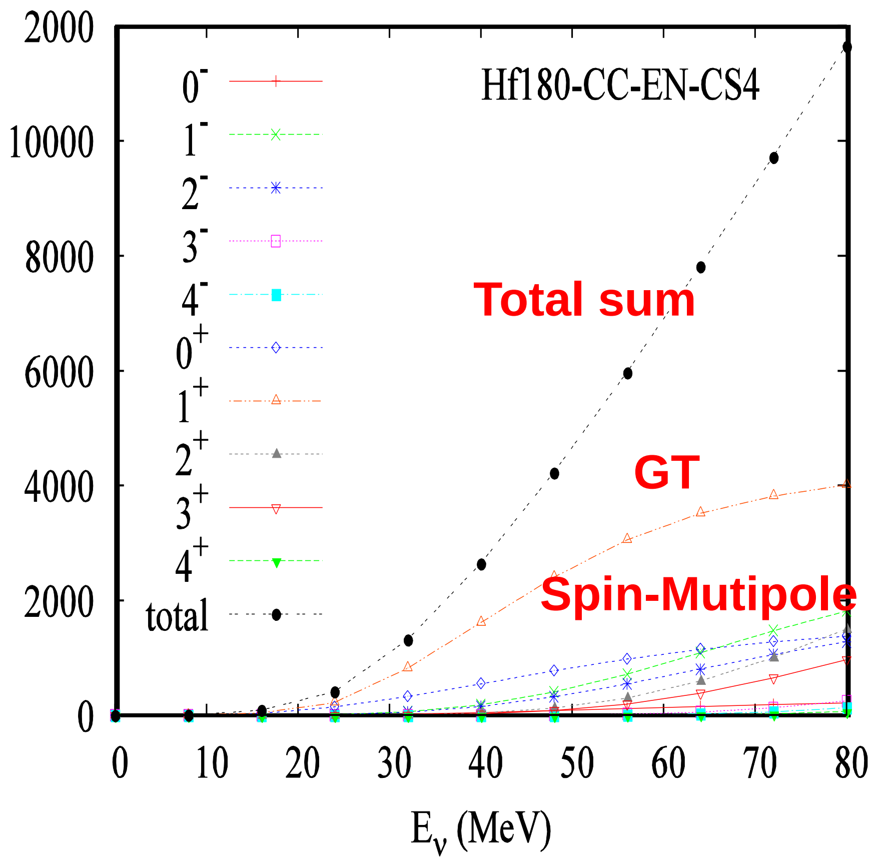
Cheoun, et al., PRC81 (2010), 028501; PRC82 (2010), 035504: J. Phys. G37 (2010), 055101; PRC 83 (2011), 028801:
Suzuki, et al., PR C74 (2006), 034307; PR C67, 044302 (2003). J. Phys. G40 (2013), 083101.

GT and Forbidden Transitions, equally important !

Calibrated by unique data on $^{12}C(\nu_e,e^-)^{12}N$.



$^{180}Hf + \nu \rightarrow ^{180}Ta + e^-$ (CC)



Connection among CEX Reaction-β decay-Astronomy-Cosmology

K. Yako et al., PRL 103 (2009) 012503.

B(GT$^{+/-}$) distribution

Shell model …

with quenched operator

Spectra agree qualitatively up to …

(p,n) : E_x = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.

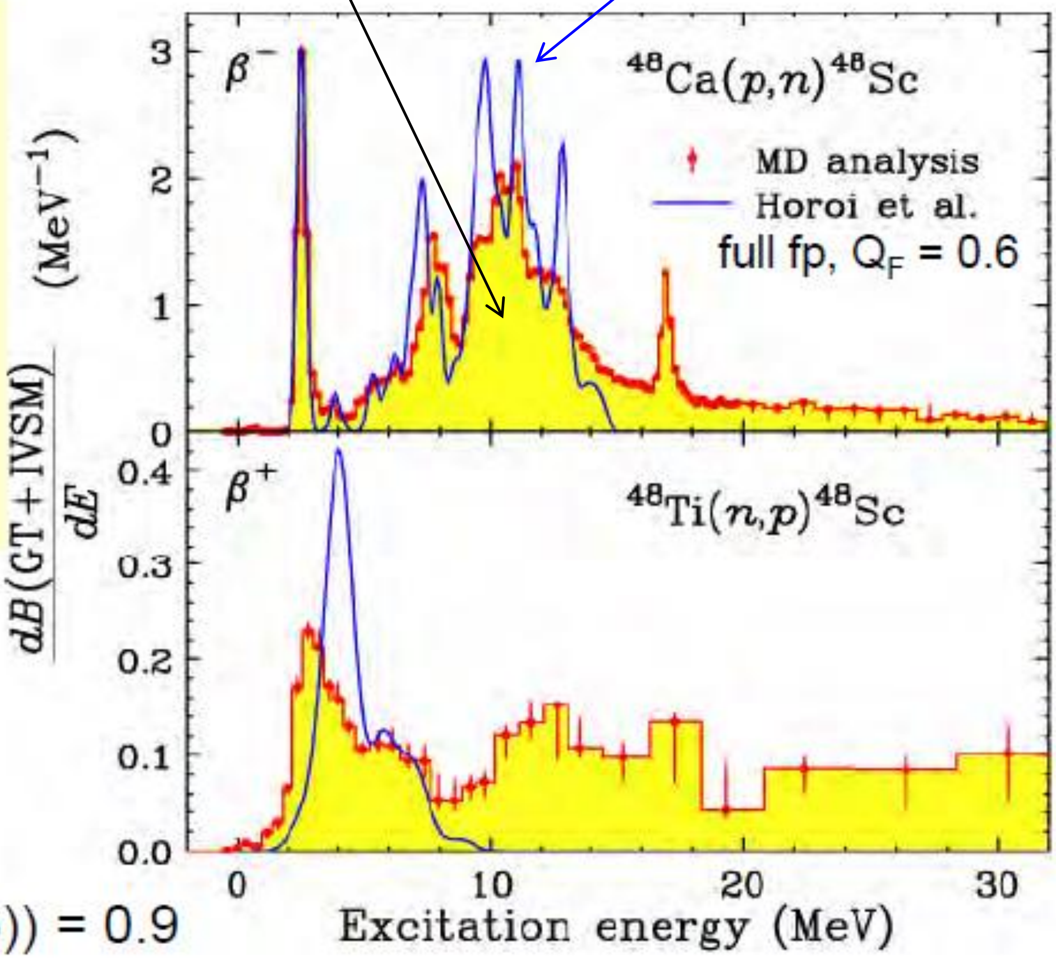
(n,p) channel :

ΣB(GT$^+$;exp) = 1.9±0.3…

(w subtraction of IVSM)

↕

ΣB(GT$^+$;ShellModel(Q_F=0.6)) = 0.9



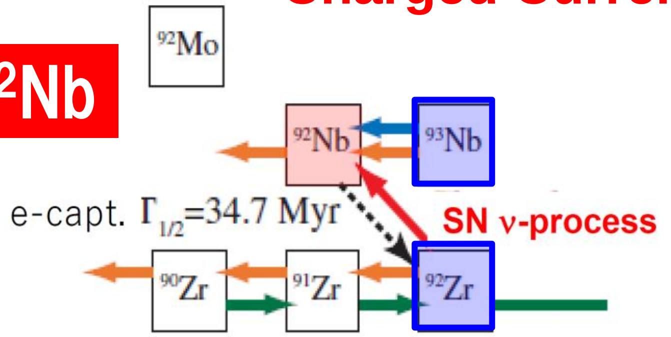
Experiment (RCNP, Osaka)

Shell model (theory)

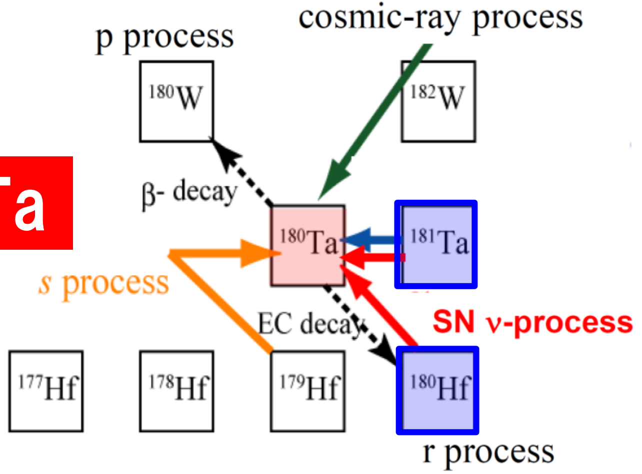
Woosley, Hartmann, Hoffman, & Haxton, ApJ 356 (1990), 272; Heger et al., PL B606 (2005), 258; Hayakawa, Kajino et al., PR C81 (2010), 052801®; PR C82 (2010), 058801; ApJL 779 (2013), L1; Kajino, Mathews & Hayakawa, JoP G41 (2014) 044007; Suzuki & Kajino, JoP G40 (2013), 083101; ++

Charged Current on ν_e

^{92}Nb



^{180}Ta

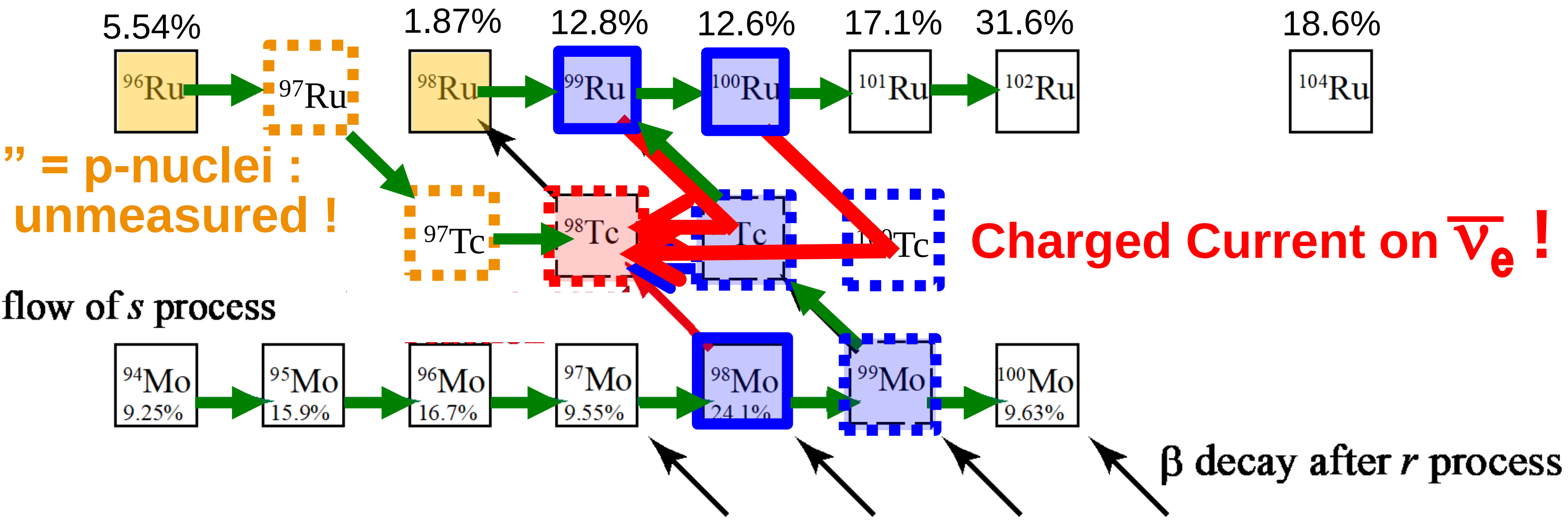


^{98}Tc is sensitive to $\overline{\nu}_e$!

Hayakawa, Kajino et al., PRL 121 (2018), 102701.

^{98}Tc decays to ^{98}Ru in 4.2 × 10^6 y, and meteoritic ^{98}Ru-isotope anomaly is predicted.

“Seeds” = p-nuclei : (n,γ) : unmeasured !

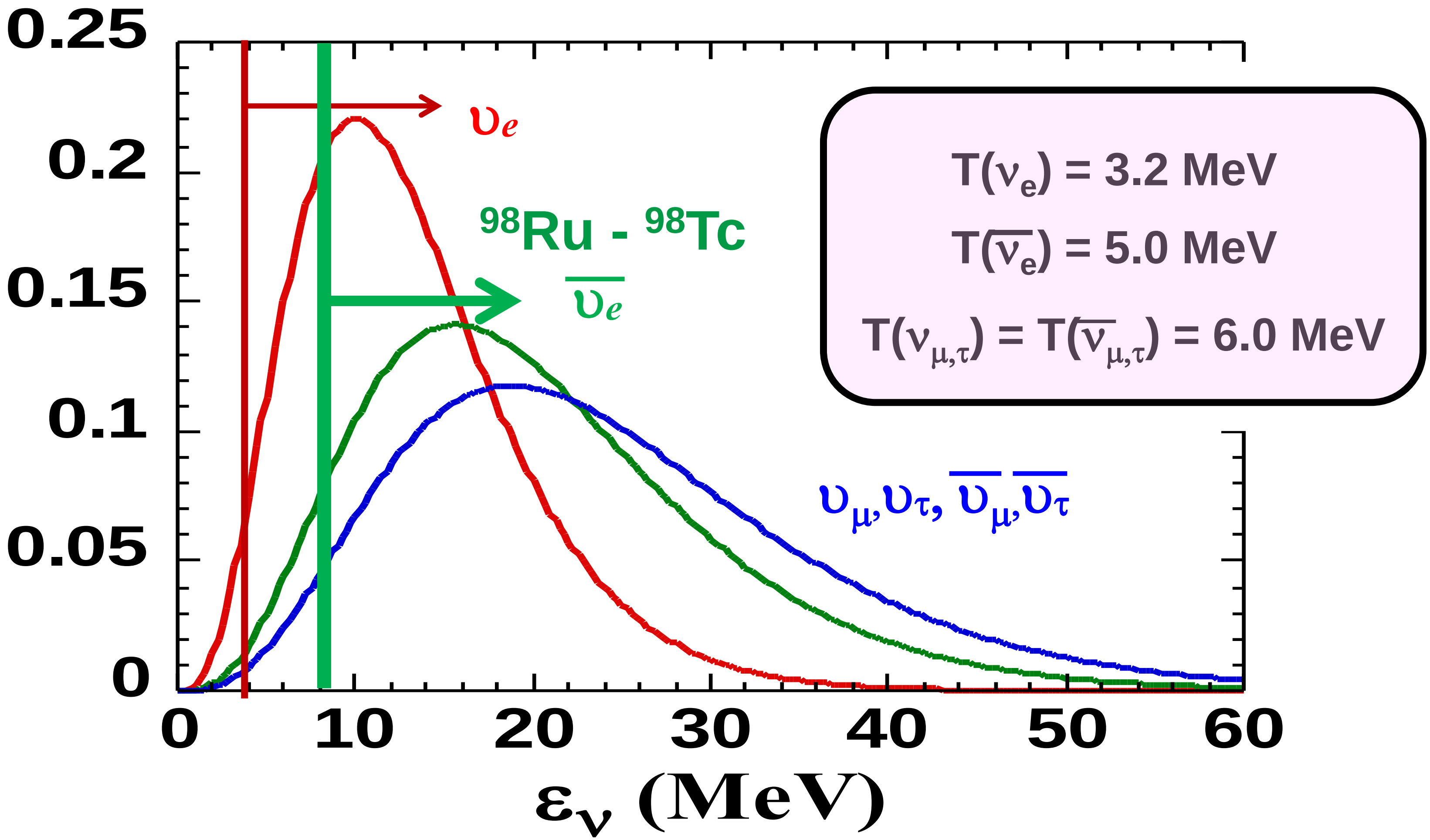


Charged Current on $\overline{\nu}_e$!

Neutrino Energy Spectra

Kajino, Mathews & Hayakawa, J. Phys. G41 (2014), 044007;
Hayakawa, Kajino et al., Phys. Rev. Lett. 121 (2018), 102701.

$T(\nu_e) < T(\overline{\nu_e}) < T(\nu_x)$ $x = \nu_\mu, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$



$T(\nu_e) = 3.2$ MeV

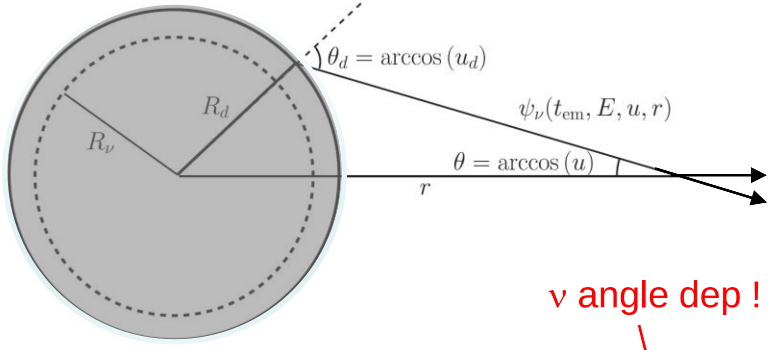
$T(\overline{\nu_e}) = 5.0$ MeV

$T(\nu_{\mu,\tau}) = T(\overline{\nu_{\mu,\tau}}) = 6.0$ MeV

MSW + Collective ν Oscillations — Many Body Quantum Effect

Balantekin, Pehlivan & Kajino, PR D84 (2011), 065008; PR D90 (2014), 065011; PR D98 (2018), 083002
Duan, Fuller, Carlson & Qian, PRL 97 (2006), 241101; Fogli, Lisi, Marrone & Mirizzi, JCAP 12 (2007) 010.

proto-neutron star (ν–sphere)



Sasaki, Kajino, Takiwaki, Hayakawa, Balantekin and Pehlivan, PR D96 (2017), 043013

$$\begin{cases} i\dfrac{d\psi_\nu}{dt} = \left(H_{\rm v} + H_e + H_\nu\right)\psi_\nu(t_{\rm em}, E, u, r), \\ H_{\rm v} = U\dfrac{M^2}{2E}U^\dagger, \\ H_e = \sqrt{2}G_F n_e(r)\,{\rm diag}(1,0,0), \end{cases}$$

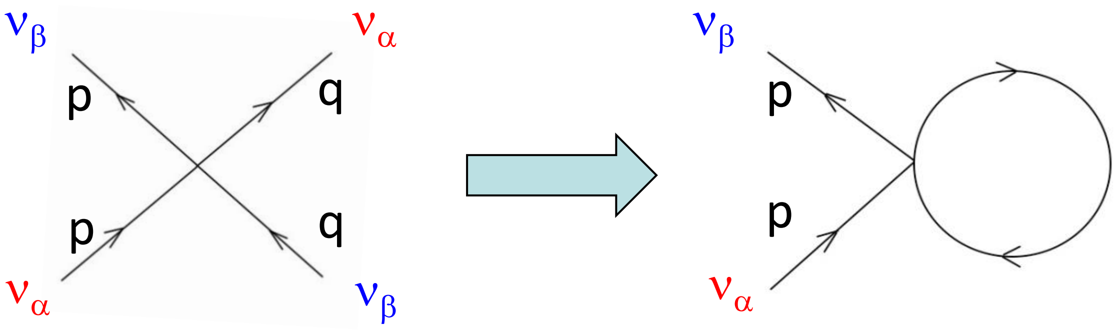
Vacuum

MSW

ν angle dep !

$$H_\nu = \sqrt{2}G_F\sum_\alpha\int \underline{dE'd\Omega'(1-uu')}\left[\frac{d^2n_{\nu_\alpha}}{dE'd\Omega'}\rho_{\nu_\alpha}(t'_{\rm em}, E', u', r) - \frac{d^2n_{\bar\nu_\alpha}}{dE'd\Omega'}\rho^*_{\bar\nu_\alpha}(t'_{\rm em}, E', u', r)\right].$$

Collective Oscill. due to coherent scattering/self-interactions



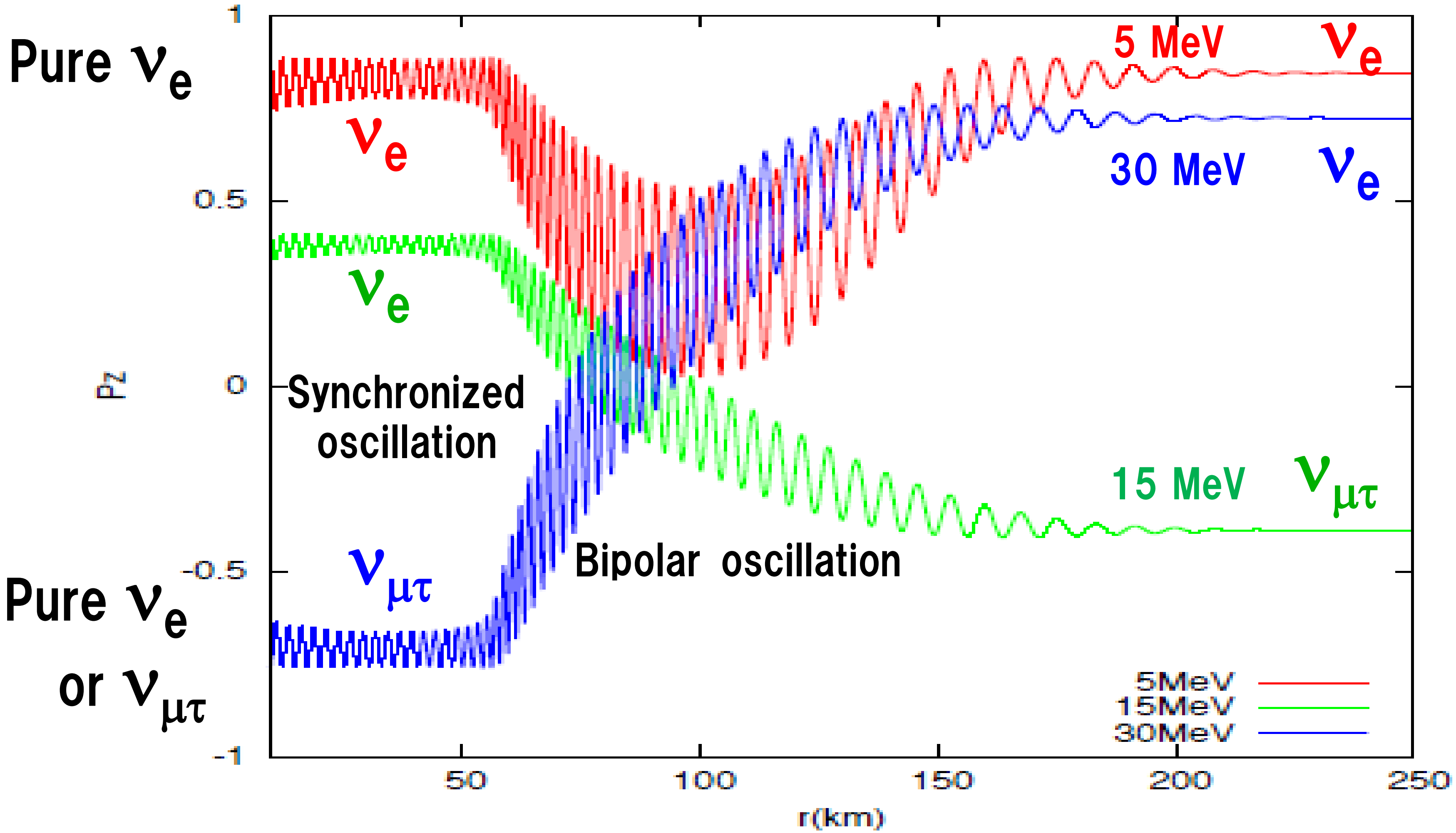
α, β = e, μ, τ

10^{48} ν's with 3-flavors & multi-angles ! → Mean Field Approx.

Calculated Collective (Self-int.) ν Flavor Oscillation

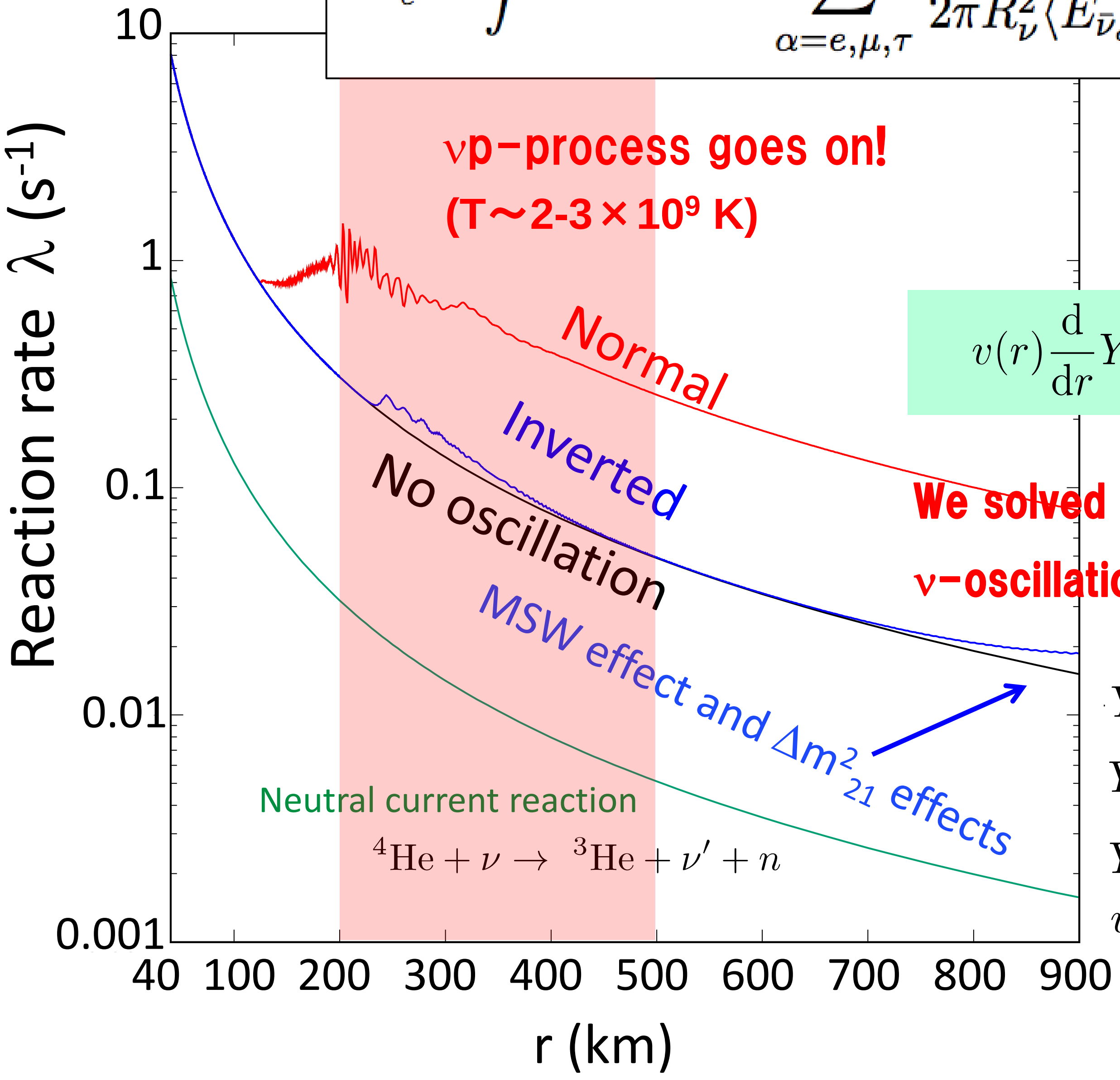
Collective ν–Flavor Oscillation induces "Eneregy Spectral Swapping."

Balantekin, Pehlivan & Kajino, PR D84 (2011), 065008; PR D90 (2014), 065011.
Birol, Pehlivan, Balantekin & Kajino, PR D98 (2018), 083002.
Sasaki, Kajino, Takiwaki, Hayakawa, Balantekin & Pehlivan, PR D96 (2017), 043013.



Continuous Collective ν−Oscillation Effect at 200 km < r !

$$\lambda_{\bar{\nu}_e} = \int \mathrm{d}E\, \mathrm{d}\cos\theta \sum_{\alpha=e,\mu,\tau} \frac{L_{\bar{\nu}_\alpha}}{2\pi R_\nu^2 \langle E_{\bar{\nu}_\alpha} \rangle} f_{\bar{\nu}_\alpha}(E) \bar{\rho}_{ee}(E, \theta_R) \sigma_{\bar{\nu}_e}(E)$$



Charged current reaction

$$\overline{\nu}_\mathrm{e} + p \rightarrow \textcircled{n} + \mathrm{e}^+$$

$$v(r) \frac{\mathrm{d}}{\mathrm{d}r} Y_n = \lambda_{\bar{\nu}_e} Y_p + \lambda_{\nu\nu'} Y_{^4\mathrm{He}} + \mathrm{Other}$$

We solved coupled evolution of collective ν−oscillation, Y_e, and nucleosynthesis.

Y_n … neutron abundance

Y_p … proton abundance

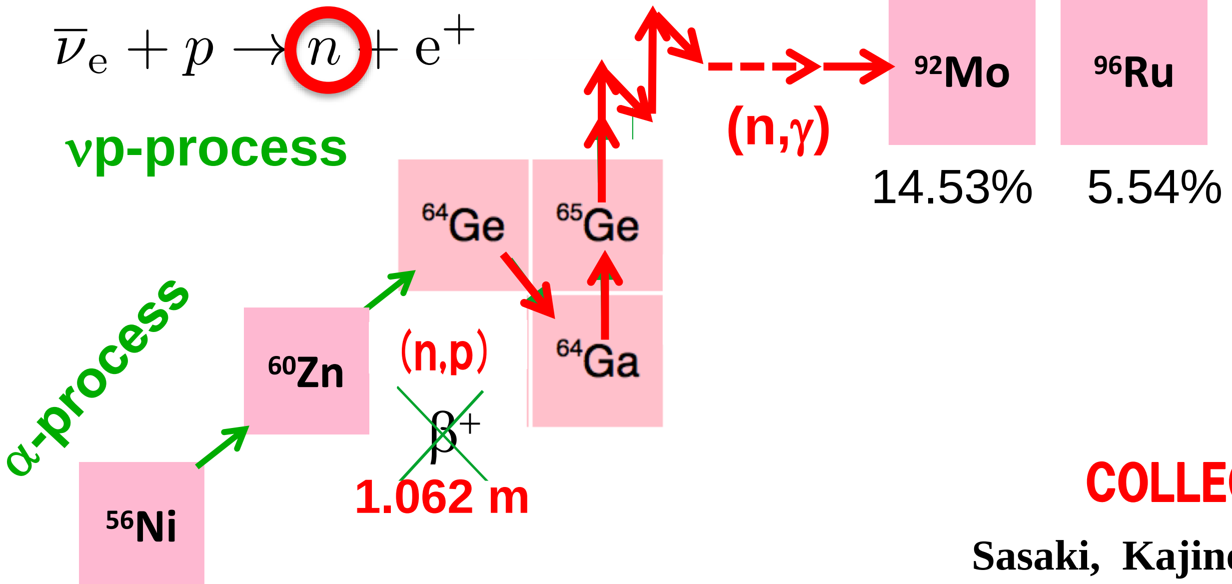
$Y_{^4\mathrm{He}}$ … helium4 abundance

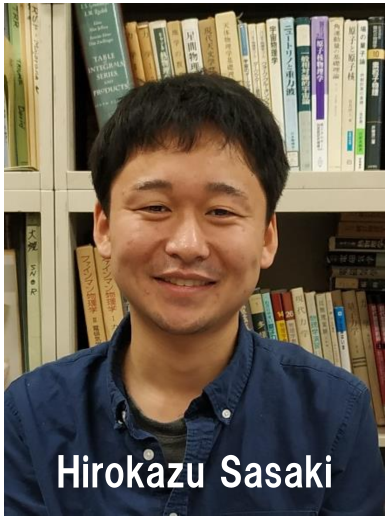
$v(r)$ … gas velocity

νp-process

C. Freohlich, et al., PRL 96 (2006), 142502.

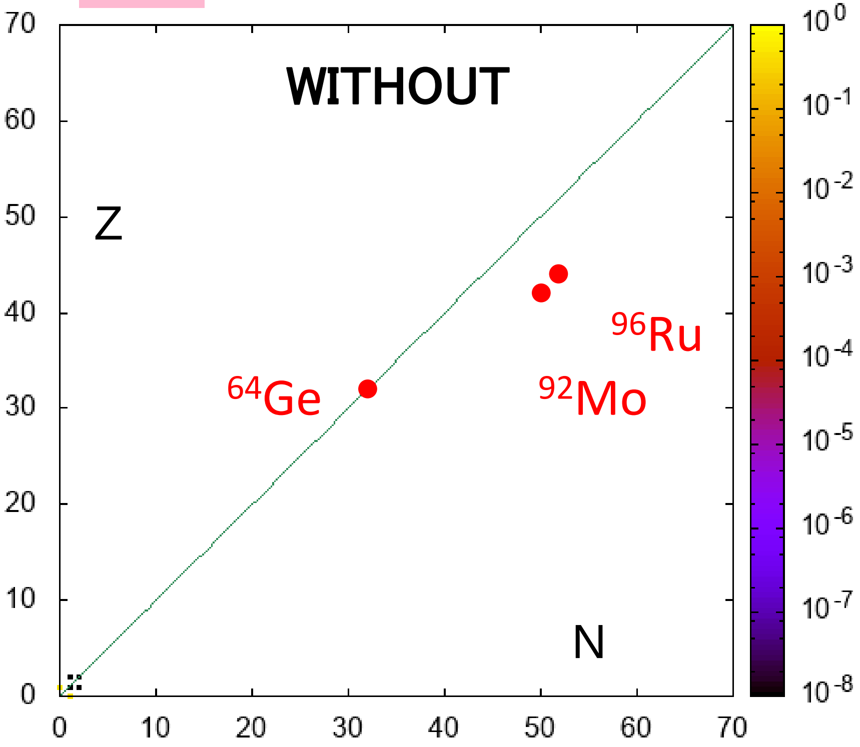
$$\overline{\nu}_e + p \rightarrow n + e^+$$

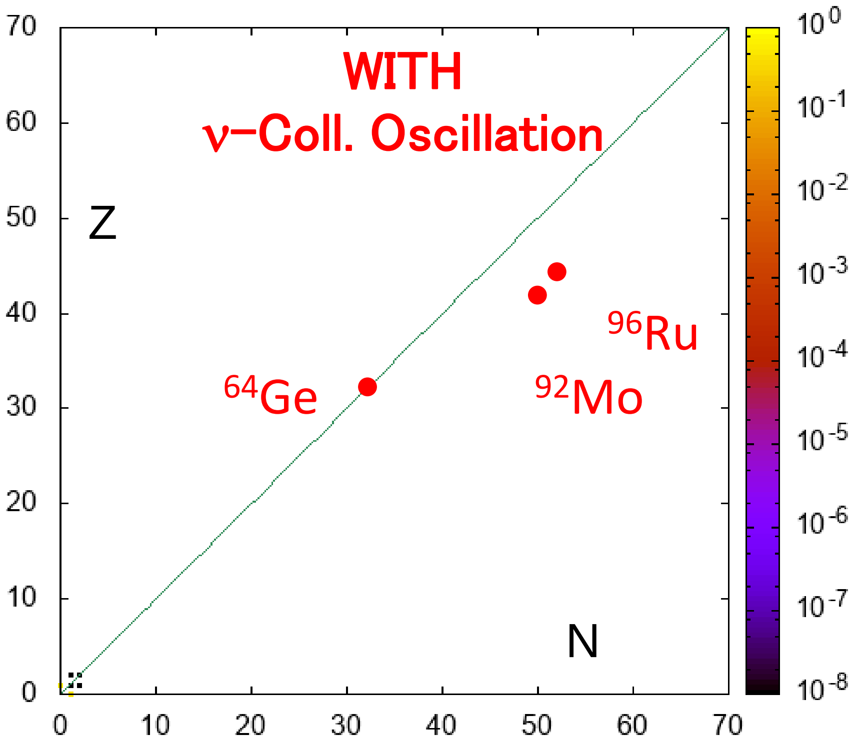




COLLECTIVE ν−oscillation

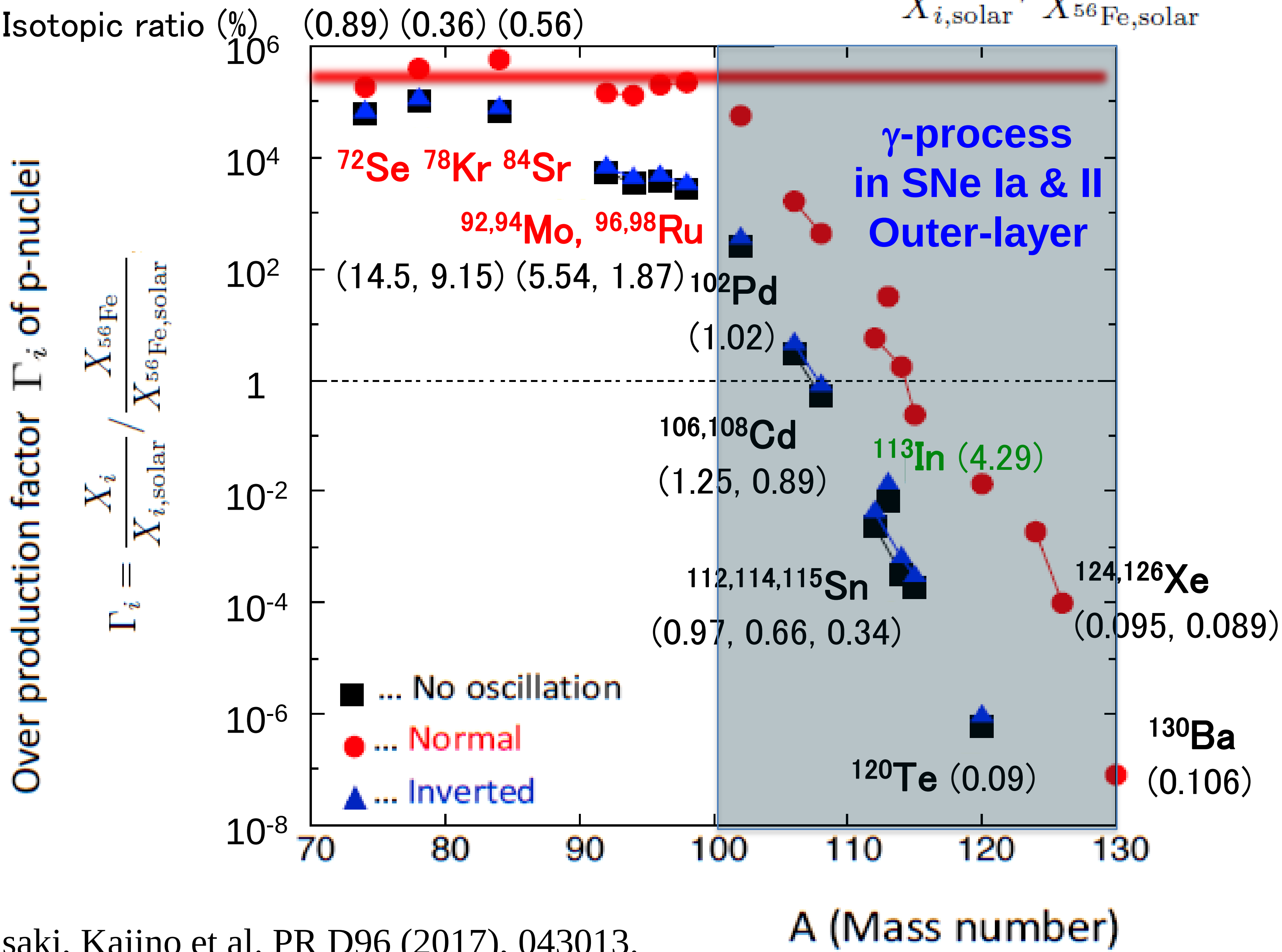
Sasaki, Kajino et al. PR D96 (2017), 043013.





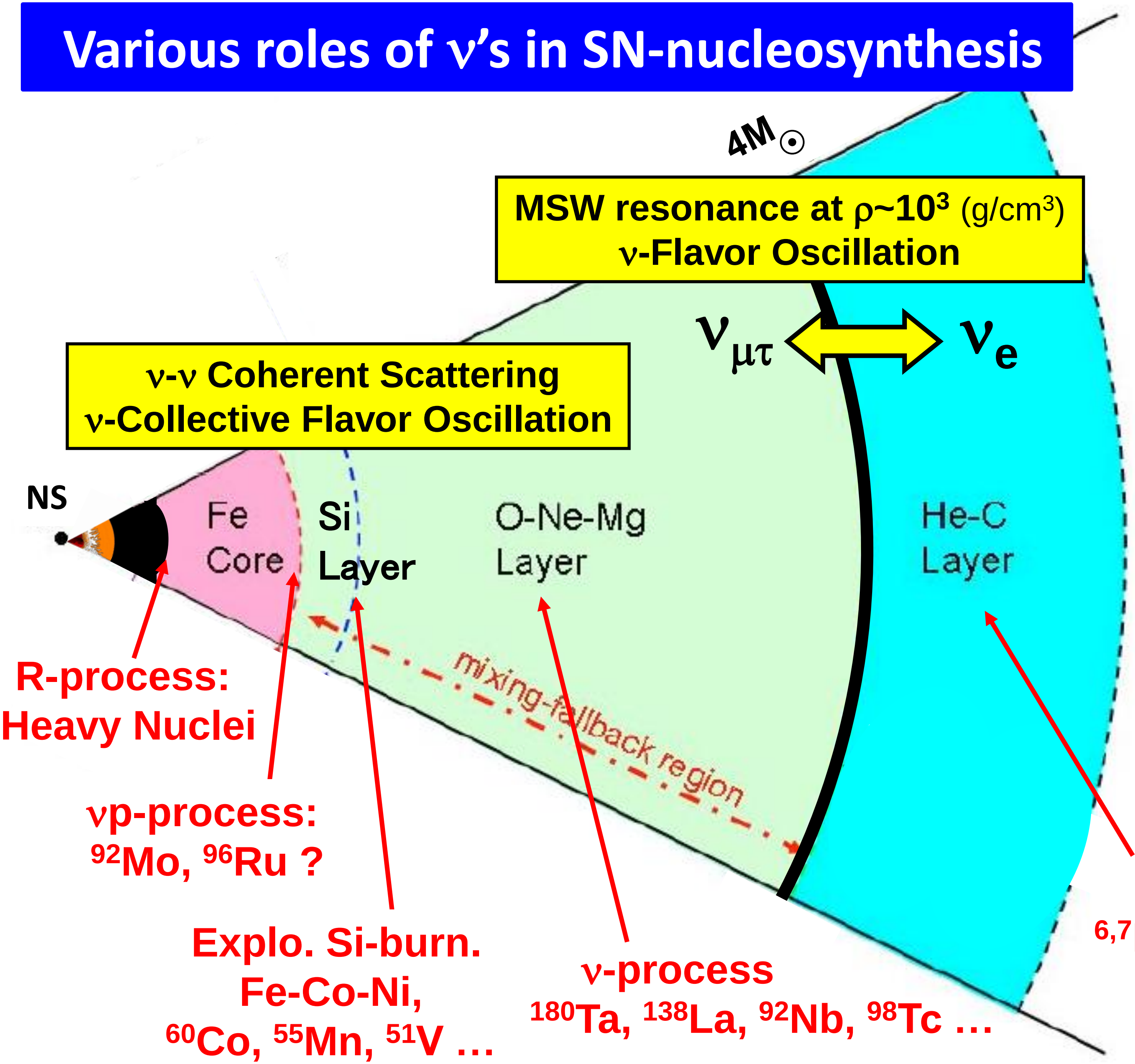
P−Nuclei /S.S. Abund.

$$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} \Big/ \frac{X_{^{56}\mathrm{Fe}} + X^{\text{Si-burn.}}_{^{56}\mathrm{Fe}}}{X_{^{56}\mathrm{Fe,solar}}}$$



Sasaki, Kajino et al. PR D96 (2017), 043013.

Various roles of ν's in SN-nucleosynthesis



MSW resonance at ρ~10^3 (g/cm^3)
ν-Flavor Oscillation

ν-ν Coherent Scattering
ν-Collective Flavor Oscillation

R-process:
Heavy Nuclei

νp-process:
^{92}Mo, ^{96}Ru ?

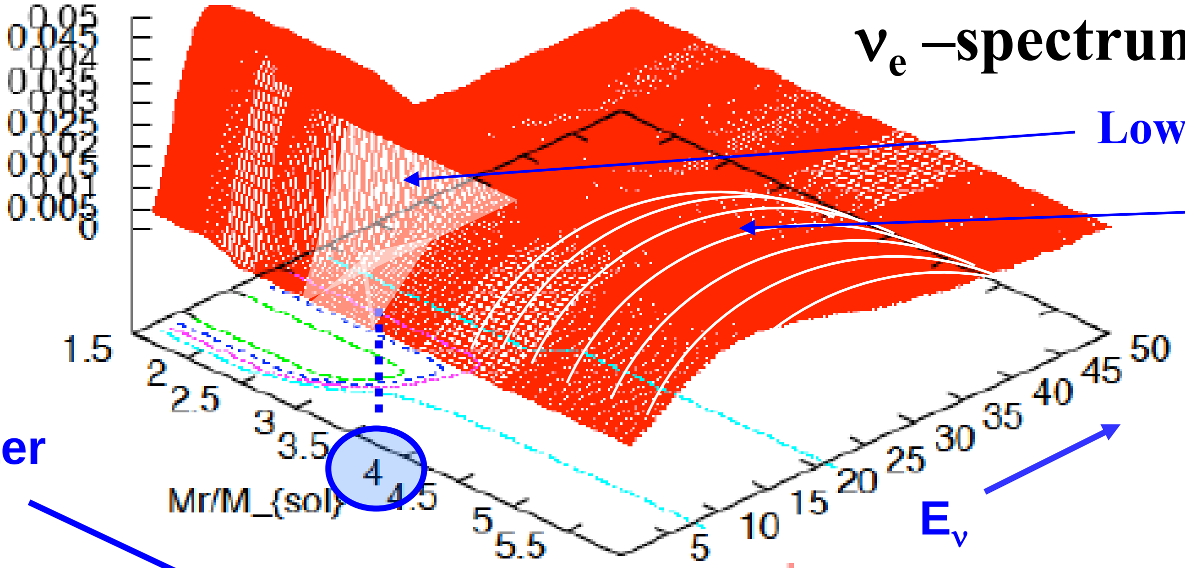
Explo. Si-burn.
Fe-Co-Ni,
^{60}Co, ^{55}Mn, ^{51}V …

ν-process
^{180}Ta, ^{138}La, ^{92}Nb, ^{98}Tc …

ν-process:
^{6,7}Li, ^{9}Be, ^{10,11}B …


Xingqun Yao

Neutrino Oscillation (MSW Effect) through propagation



ν_e –spectrum

Low-E comp. disappears !

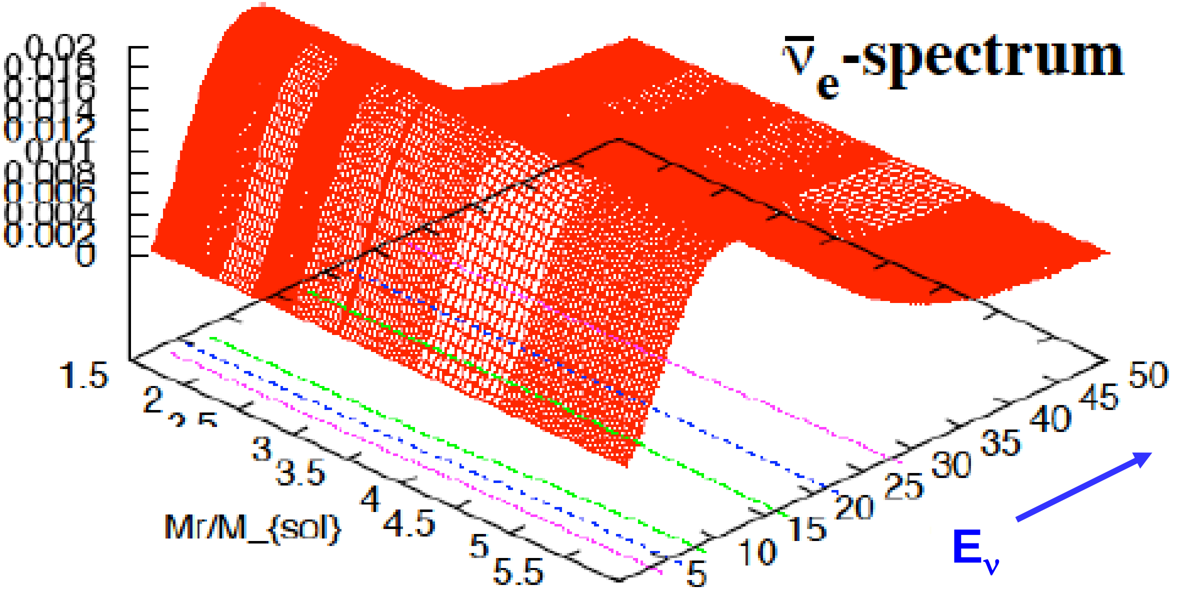
High-E comp. appears !

$\tau_\mu, \tau_\tau \longrightarrow \tau_e$

E_ν

Center

outside



$\bar{\nu}_e$-spectrum

E_ν

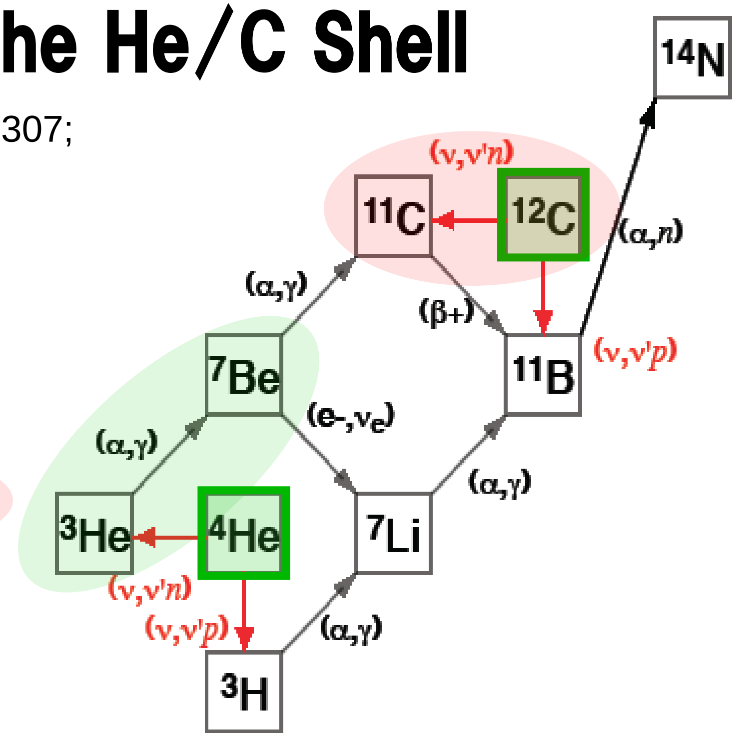
Parameters:

25M_{solar} progenitor SN model
(Hashimoto & Nomoto 1999)

- $\sin^2 2\theta_{13} = 0.04$
- $\varDelta m_{13}^2 = 2.4\text{x}10^{-3}$ eV^2
- $L_\nu = 3\text{x}10^{53}$ erg, $\tau_\nu = 3$ sec
- $T_{\nu e}$=3.2MeV, $T_{\nu e}$=5.0MeV, $T_{\nu\mu\tau}$=6.0MeV

^{7}Li and ^{11}B are produced in the He/C Shell

Suzuki, Chiba, Yoshida, Kajino and Otsuka, PRC74 (2006), 034307;
Yoshida, Suzuki, Chiba, Kajino, et al., ApJ 686 (2008), 448;
Suzuki and Kajino, J. Phys. G40 (2013), 083101;
Hayakawa, Kajino et al., PRL 121 (2018), 102701;
Ko, Cheoun, Kajino et al. (2019), submitted.

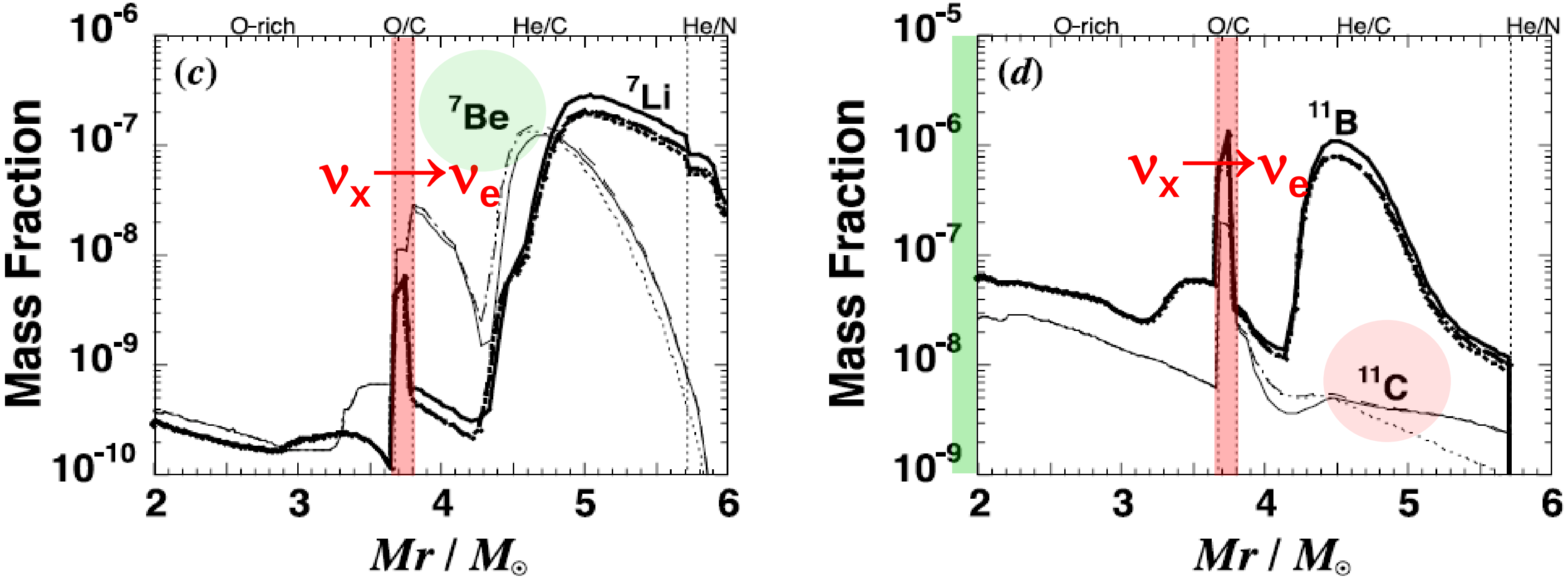


$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}$, $^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}$, $^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$

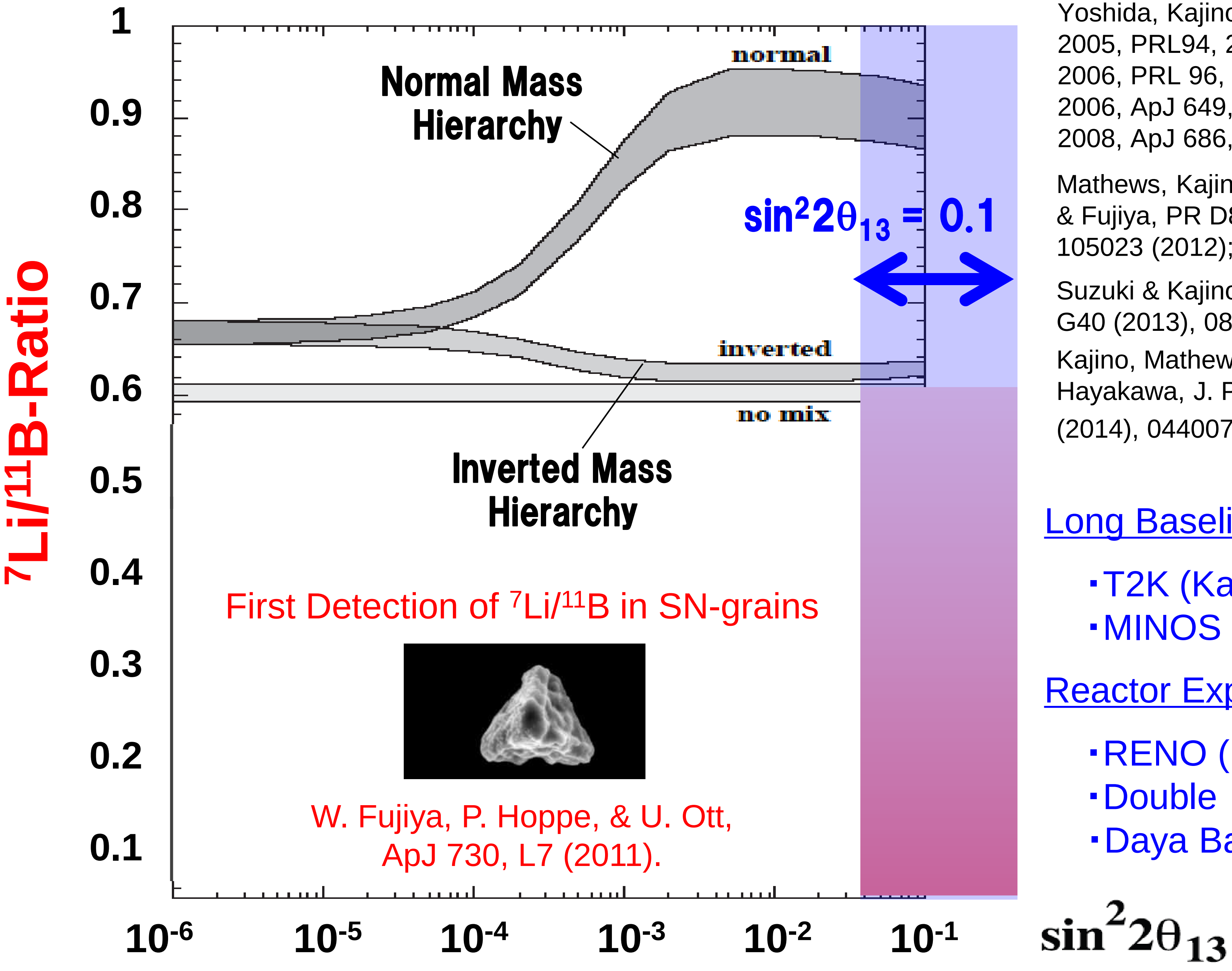
$^{4}\mathrm{He}(\nu_e,e^- p)^{3}\mathrm{He}$, $^{4}\mathrm{He}(\bar{\nu}_e,e^+ n)^{3}\mathrm{H}$, $^{12}\mathrm{C}(\nu_e,e^- p)^{11}\mathrm{C}$,

MSW high-density resonance

(NORMAL Hierarchy)



Nucleosynthesis to constrain Mass Hierarchy



First Detection of ^{7}Li/^{11}B in SN-grains

W. Fujiya, P. Hoppe, & U. Ott,
ApJ 730, L7 (2011).

Yoshida, Kajino et al.
2005, PRL94, 231101;
2006, PRL 96, 091101;
2006, ApJ 649, 319;
2008, ApJ 686, 448.

Mathews, Kajino, Aoki & Fujiya, PR D85, 105023 (2012);

Suzuki & Kajino, J. Phys. G40 (2013), 083101;

Kajino, Mathews, Hayakawa, J. Phys. G41 (2014), 044007.

Long BaselineExp.:

- T2K (Kamioka)
- MINOS

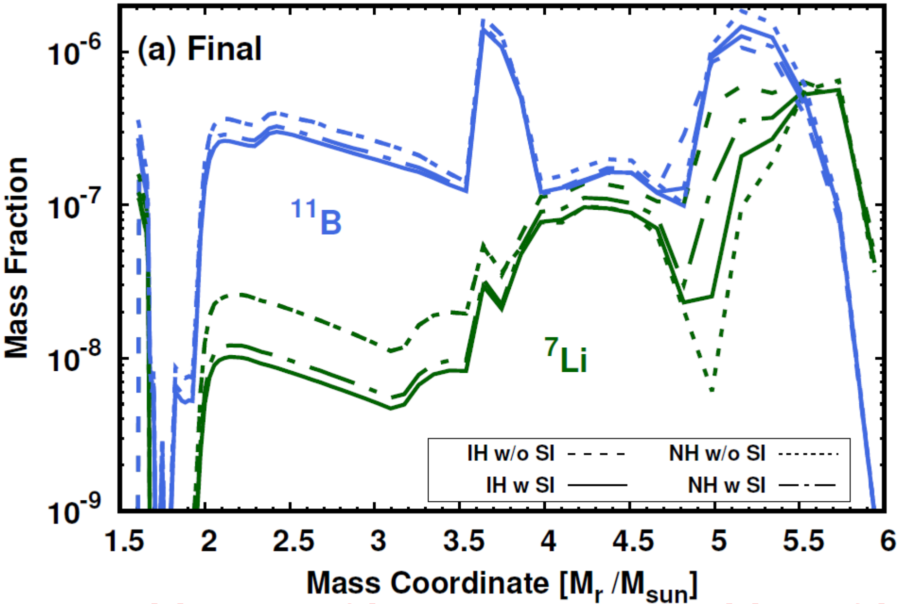
Reactor Exp.:

- RENO (KOREA)
- Double CHOOZ
- Daya Bay

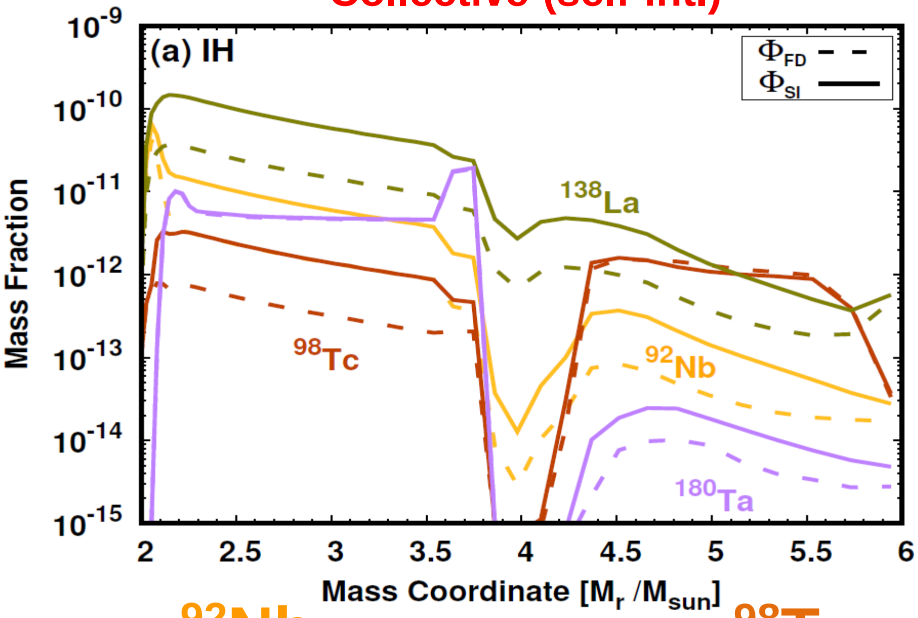
ν-process Nucleosynthesis : ^{7}Li, ^{11}B, ^{92}Nb, ^{98}Tc, ^{138}La , ^{92}Nb

Hayakawa, Kajino et al., PRL 121 (2018), 102701; Ko, Cheoun, Kajino et al., ApJ Lett. 891 (2020), L24.

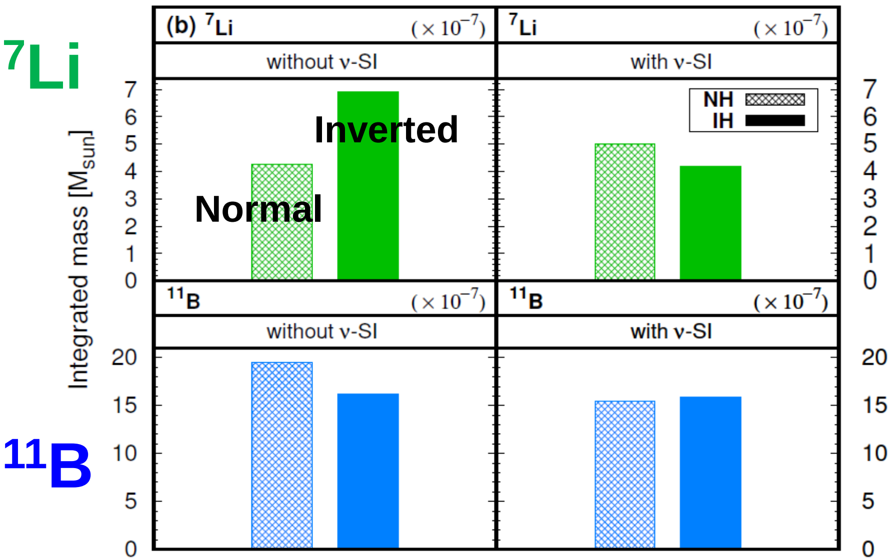
Collective (self-int.) + MSW



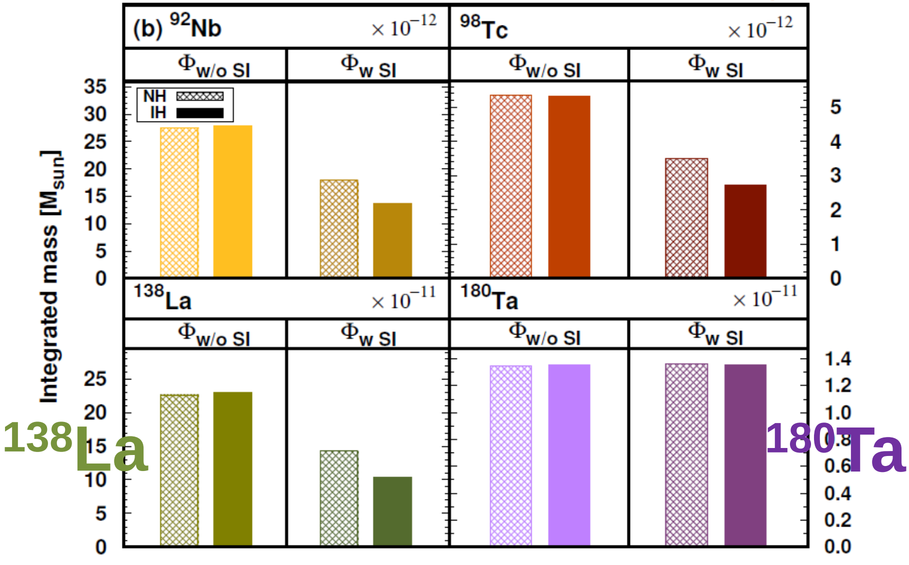
Collective (self-int.)



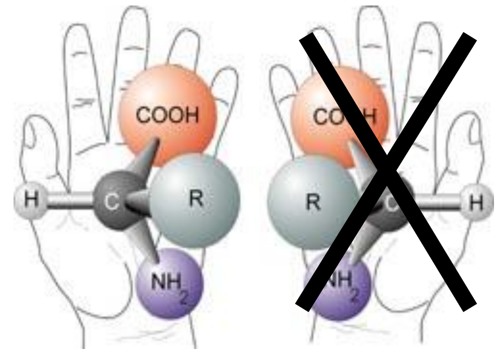
Without self-int. **With self-int.**



^{92}Nb **^{98}Tc**



Mystery in Life !



Origin of L-Chirality of Amino Acids ?

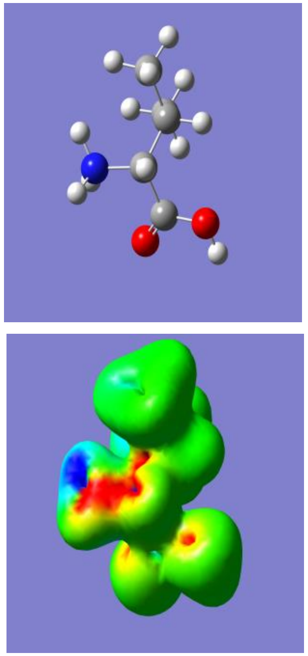
Famiano, Boyd, Kajino, Onaka, et al. Astrobio. 10 (2010), 561; Int. J. Mol. Sci. 12 (2011), 3432; Symm. 6 (2014), 909; Astrobio. 18 (2018) 190; ApJ 856 (2018) 26; Sci. Rep. 8 (2018), 8833; Symm. 11 (2019) 23; Astrobio. 20 (2020), 964.

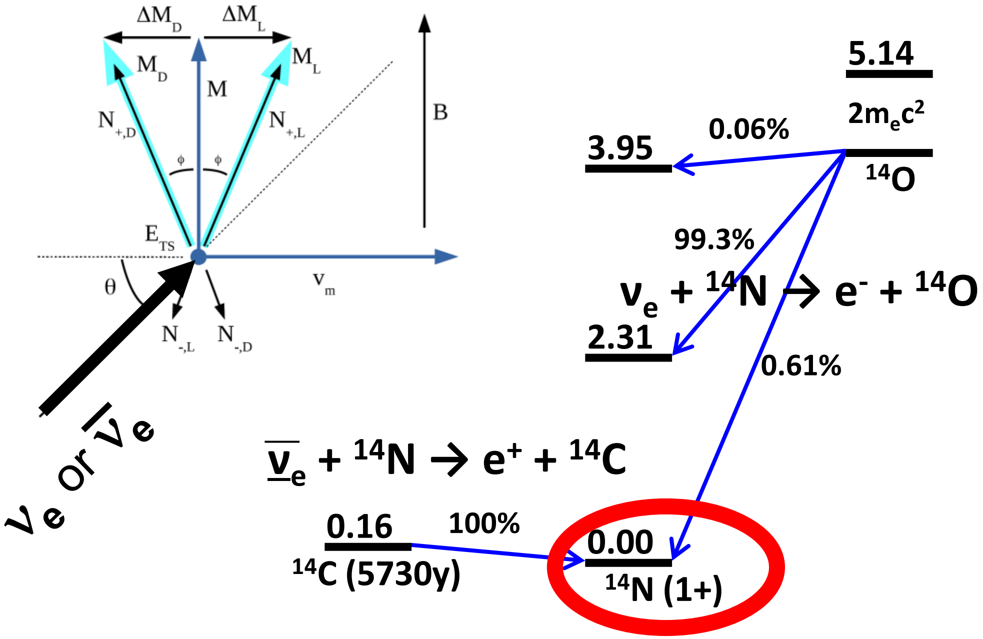
EW Coupling of Nuclei & Molecules under B-Field → Chiral Selection

- Magnetic B-field of NS, BH, NSM orients ^{14}N(s=1) via *nuclear* magnetic dipole moment.
- Meteoroid & amino acids are exposed to B-field & induced E-field.
- E-field shifts the electrons, so affects the *molecular* electric dipole moment.

→ ***These operate opposite for two chiralities.***

Quantum molecular calculations for Valine





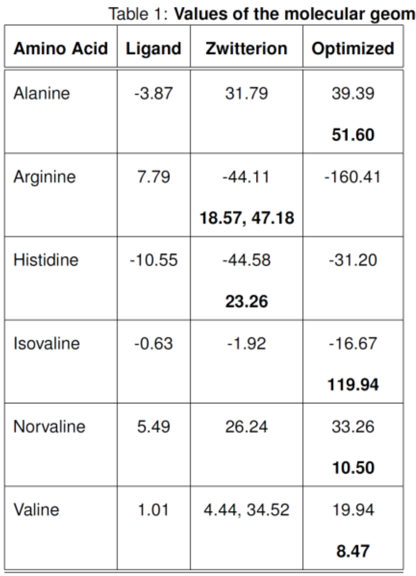
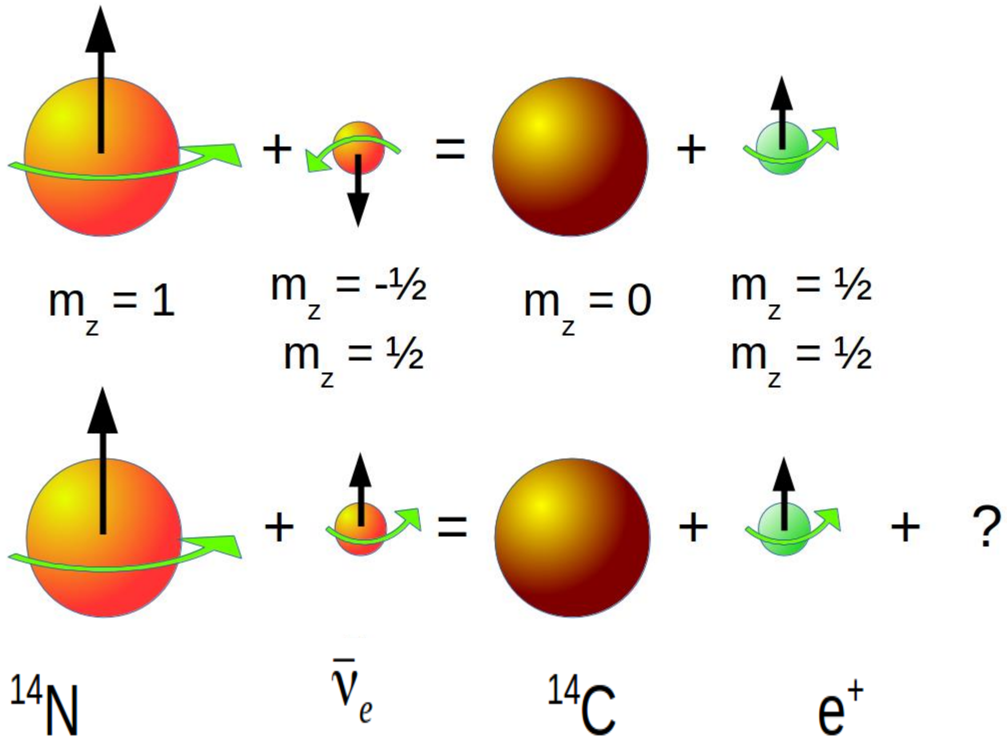


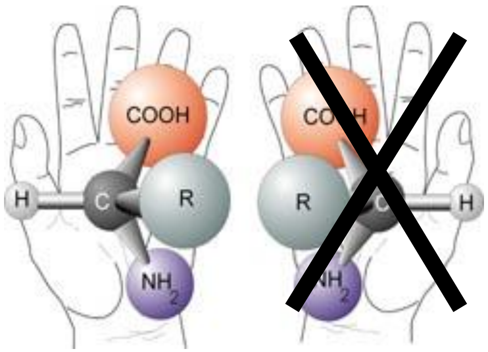
Table 1: **Values of the molecular geometry pa**

Amino Acid	Ligand	Zwitterion	Optimized
Alanine	-3.87	31.79	39.39 **51.60**
Arginine	7.79	-44.11 **18.57, 47.18**	-160.41
Histidine	-10.55	-44.58 **23.26**	-31.20
Isovaline	-0.63	-1.92	-16.67 **119.94**
Norvaline	5.49	26.24	33.26 **10.50**
Valine	1.01	4.44, 34.52	19.94 **8.47**

Effect of ^{14}N and Antineutrino Spin



Cross section for destroying spin-aligned ^{14}N is less than for anti-aligned ^{14}N by an order of magnitude (or two).



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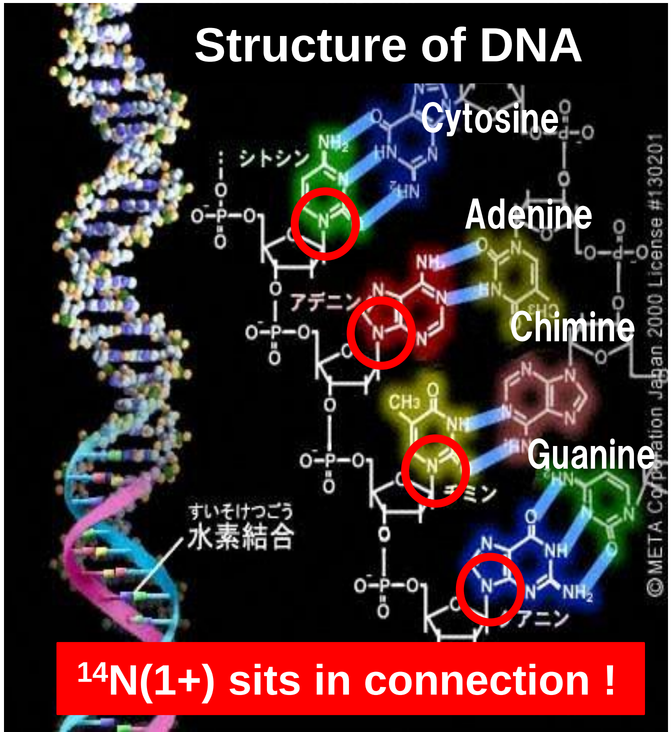
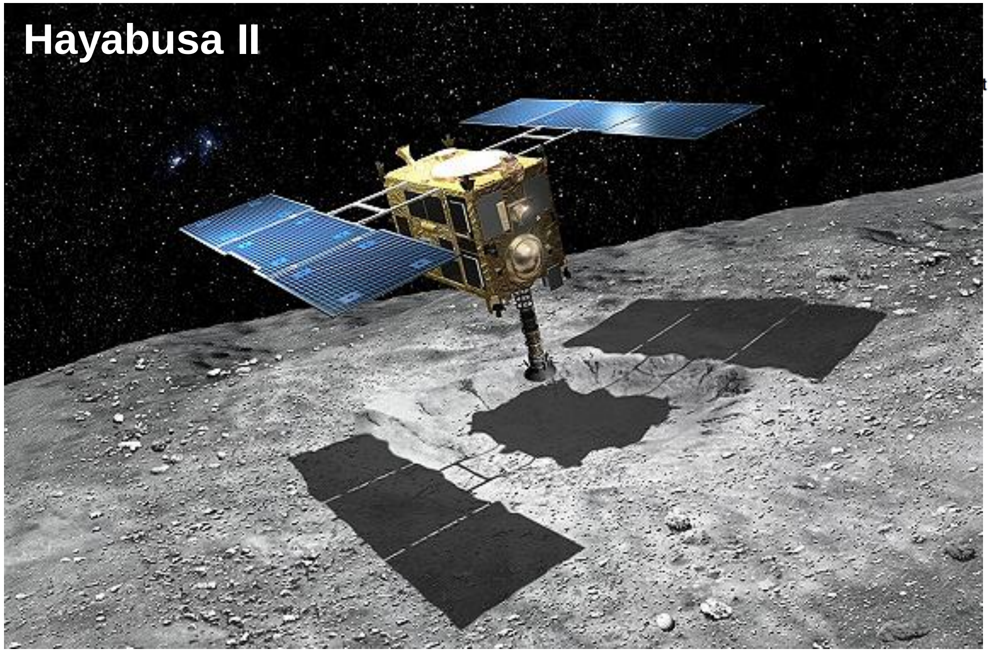

Structure of DNA

^{14}N(1+) sits in connection !

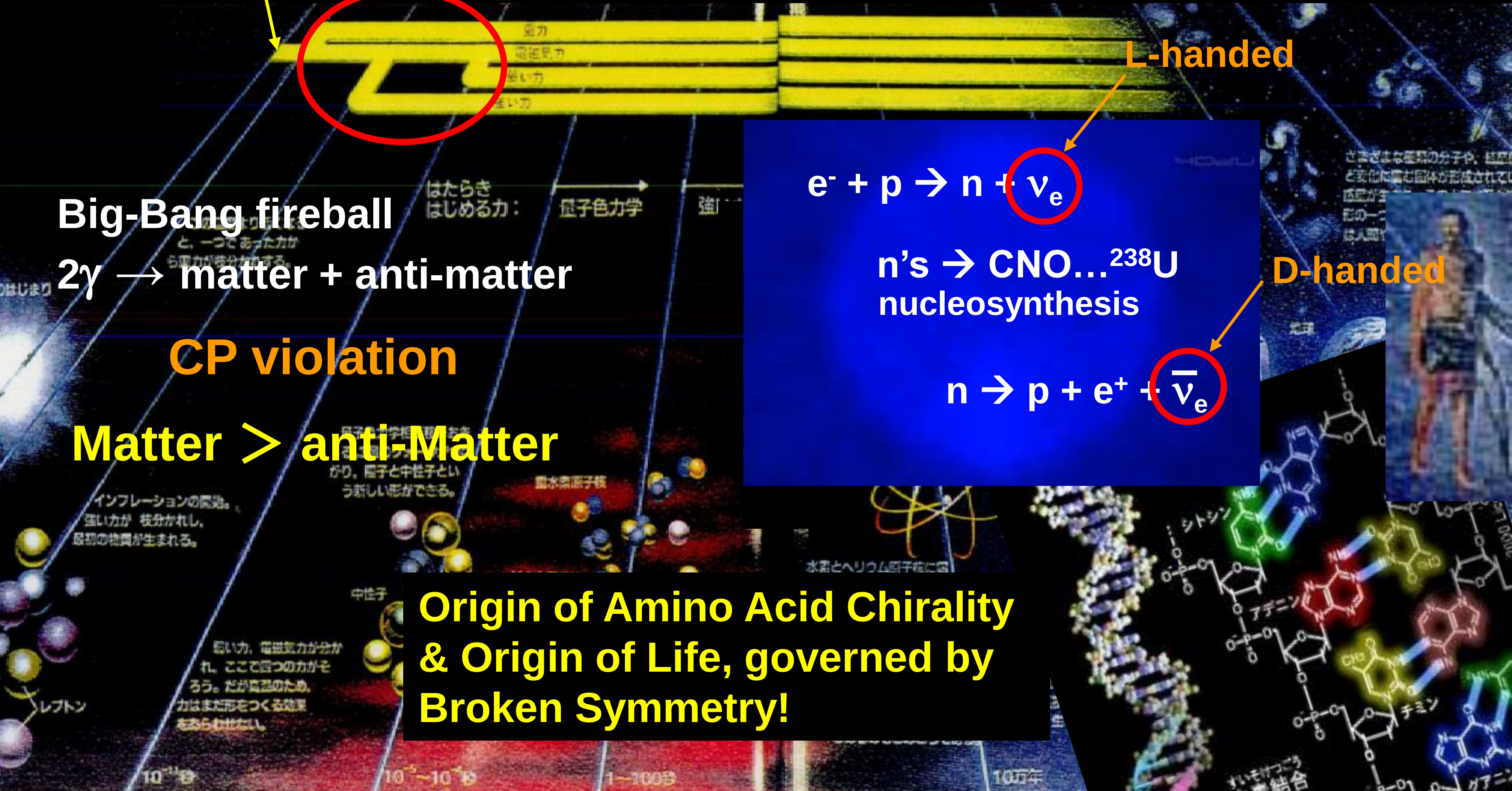

Hayabusa II

Highest symmetry
Unified force

Symmetry
was
Broken.

Beginning of time → Cosmic evolution → Present

0 → Time



Big-Bang fireball

$2\gamma \longrightarrow \text{matter} + \text{anti-matter}$

CP violation

Matter ＞ anti-Matter

$e^- + p \rightarrow n + \nu_e$

n's → CNO…^{238}U
nucleosynthesis

$n \rightarrow p + e^+ + \bar{\nu}_e$

Origin of Amino Acid Chirality & Origin of Life, governed by Broken Symmetry!

Summary

◆ Big-Bang Lithium Problem

→ PMF Fluctuations (CMB) + Nucl. Phys. + DM Particle Phys. towards solution !

◆ Heavy Elements in the Early Galaxy were dominated by Supernovae and Collapsars, and Neutron Star Mergers have arrived later.

→ Galactic Evolution, Nuclear Processes, Neutrino Physics … !

◆ Supernova ν-process could be a probe of collective and MSW ν-oscillation effects and mass hierarchy.

→ ν-oscillation (Collective & MSW …) — Field Theoretical Approach
→ Nucl. Weak Response of ^{98}Tc, ^{180}Ta, ^{138}La, ^{92}Nb, ^{7}Li, ^{11}B …

We are in the Dawn of Multi-Messenger Astronomy & Nuclear Astrophysics.

GW — ν — Opt.-IR-X-γ — Nuclei

Gravity	Weak	Electro-magnetic	Strong

Synergy among interdisciplinary sciences is highly desirable!

Two Giants passed away!

Don’t stop challenging !
Seek for truth, work hard and help each other !
Go your own way !

Be ambitious!
Hold many tremendous dreams!
Keep trying until they come true!”

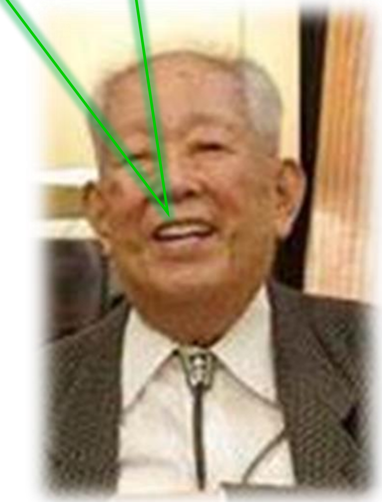
Let us enjoy
“Endless and Borderless Endeavour” in the frontier science of “Cosmology and Nuclear Astrophysics” !

Thank you !

President Akito Arima

Kajino’s mentor
in the PhD course

Two giants established a new frontier of “Neutrino Astronomy” on the synergy of physics and astronomy in early 1990.



Professor Masatoshi Koshiba

Kajino’s supervisor
in the undergraduate course